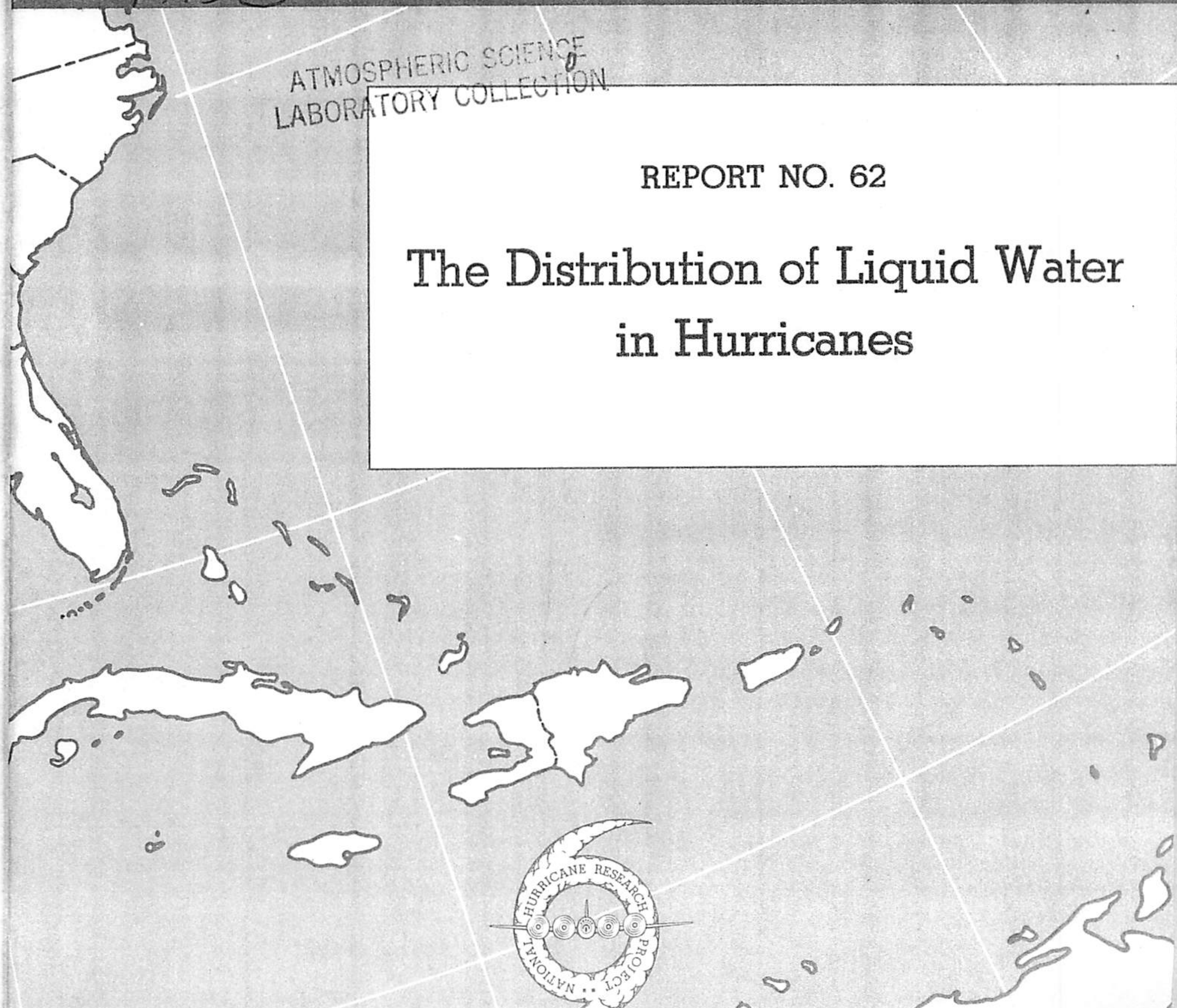
NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 62

The Distribution of Liquid Water in Hurricanes



U. S. DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 62

The Distribution of Liquid Water in Hurricanes

by

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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THE DISTRIBUTION OF LIQUID WATER IN HURRICANES

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1. INTRODUCTION

The University of Chicago Cloud Physics Laboratory has engaged in the study of the microphysics of hurricanes over the last several years. This activity has been sponsored by the U. S. Weather Bureau as a part of the program carried out by the National Hurricane Research Project.

This report is concerned with the research supported under U. S. Weather Bureau Contract Cwb-9720, entitled Cwb Hurricane Research No. 5, covering the period July 1, 1959 to June 30, 1960. Dr. R. R. Braham, Jr. of the University of Chicago served as general supervisor.

The primary responsibility of the Cloud Physics Laboratory under this contract was the evaluation and analysis of cloud physics data collected by Hurricane Project aircraft during the 1957, 1958, and 1959 operational seasons. In addition, the laboratory was to have participated in the flight operations during 1959 to the extent of providing a staff member to serve as flight observer and as advisor in the tasks of instrument calibration and data reduction for the phase of the operation pertaining to cloud physics. Since the aircraft were not equipped for the collection of cloud physics data during 1959, the energies of the Cloud Physics Laboratory were addressed entirely to the analysis of data collected during 1957 and 1958. In particular, research interest was concentrated on the evaluation and analysis of liquid-water-content measurements and related data. This work was a continuation of that undertaken under Contract No. Cwb-9484.

2. DESCRIPTION OF DATA

Collection

Water content measurements were made using both heated-wire and paper-tape liquid-water-content meters. For reasons discussed in an earlier report [2] the former is believed to underestimate seriously the water content of hurricane clouds. Therefore, the analyses were restricted to measurements made using the paper-tape instrument. These measurements, as well as the air-speed measurements needed for evaluation of the data, were continuously recorded by a Heiland oscillograph recorder. Details of the instrumentation and of the techniques used in the collection, reduction, and evaluation of the data, and a list of the available cloud physics data may be found in the forementioned report.

The hurricane flights were made by three airplanes - two B-50's and one B-47. The latter carried no cloud physics instrumentation. One of the B-50's, No. 007, was not outfitted with the paper-tape water-content meter. Therefore, only flights made by aircraft No. 032 (entitled B-flights) could be used in this study. All water-content data collected on the following flights were reduced: 70915-B (Carrie 1957); 80813-B (Becky 1958); 80825-B and 80827-B (Daisy 1958); 80924-B (Helene 1958).

Characteristics of Cloud and Water Distributions

Although many radar and photographic records were collected by the National Hurricane Research Project aircraft, only a small portion have been analyzed and the cloud structure and distribution in hurricanes are still imperfectly known. Private communications with individuals who have participated in hurricane flights indicate that the structure and distribution change during the life history of a given hurricane and vary considerably from storm to storm. In general, however, well-spaced convective bands are imbedded in widespread layers occurring at several levels, with the former occupying only a small fraction of the total area covered by the hurricane system. Radar observations also indicate a low areal density of convective clouds.

The water-content measurements suggest a similar areal distribution. On most flights the airplane encountered fairly steady water content values of 0.25 g./m.^{3}, periodically interrupted by cells of heavy concentrations of water, 1-1/2 to 3 miles in length. The water content in these cells was similar, in magnitude and variability, to that observed in convective clouds of both disturbed and fair weather [1, 7]. There was a high degree of variability along the line of flight with the water occurring in cells having widths of several hundred to a few thousand feet. Superimposed on this array were smaller-scale fluctuations. These had periods too long to be instrumental noise but which may have represented "physical noise." An example of measurements obtained in convective bands is given in figure 1.

Although water content in excess of 1 g./m.^{3} was found chiefly in the small fraction of the hurricane represented by the convective bands, water cells of moderate intensity (under 1 or 2 g./m.^{3}) were occasionally encountered during traverses through layer clouds. These cells were usually quite small - less than 500 or 600 m. in length.

Data Reduction and Analysis Techniques

Although continuous measurements were available, the data were reduced in the form of averages over 1-sec. intervals (roughly 110-125 m. in travel distance at the speed of the aircraft). This enabled examination of macro-scale features by simple mathematical manipulation of the large volume of data involved, while sufficient information on the grainy nature of the water content distributions was retained for analysis of the micro- or meso-scale variations. Computations of the power spectrum and autocorrelation coefficients are being made for a study of the micro-structure of the water distribution in convective bands. This study is now in progress but has not yet been completed.

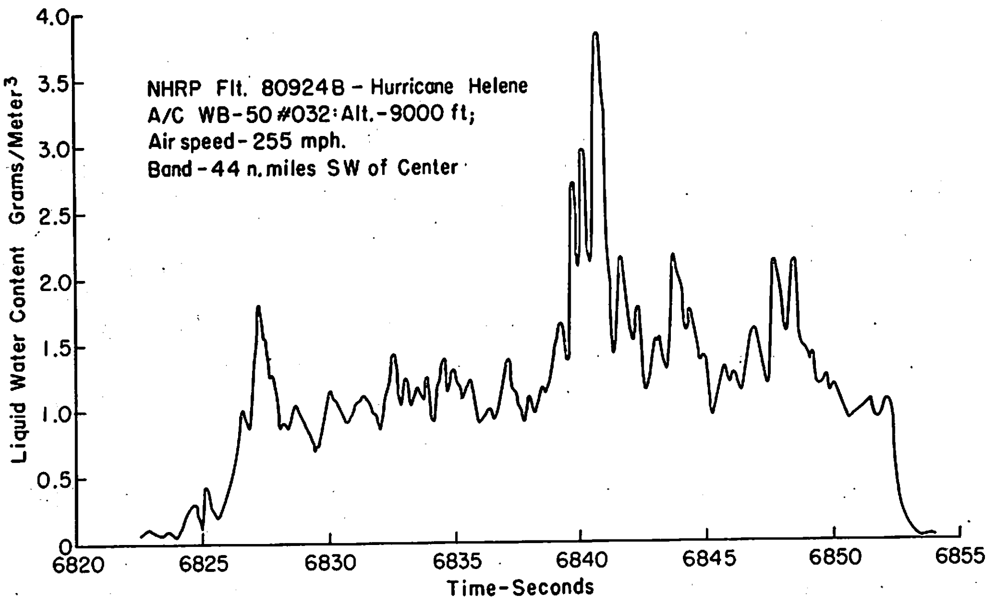


Figure 1. - An example of the water content measurements obtained in a convective band.

For the study of the macro-features of the hurricane, the 1-sec. means involve a volume of data much too large to be easily handled or absorbed, and, moreover, give more detail than is necessary. Consequently, average values of water content were computed for "homogeneous" sections, loosely defined as follows: (a) almost constant water content values with perhaps a few very small cells of variable water (duration 5 sec. or less), or (b) cloud band composed of one or more cells. The second categary was sometimes further divided when the bands were composed of several large cells having well-defined boundaries. For descriptive purposes, these averages are plotted along the flight paths in the relative coordinate system (e.g. figs. 4, 12).

Also included on these plots are the locations of radar echoes, "composited" from the radarscope photographs obtained on the flight. The task of fitting the water measurements and the radar echoes is a time consuming and difficult one because of the transient nature of the clouds. Studies by others [13, 14] indicate that the individual cloud units in convective bands last from 10 to 45 min. with an average duration of about 30 min., and that the life span of the band as a whole is of the order of 2 hr. In addition, individual clouds in a band move very rapidly - roughly with the speed of the winds [9].

Since (for the range used) the first few miles around the airplane were obscured on the radar scope by the transmitted pulse, it is necessary to interpolate between pre- and post-probe locations of the echo to fit the water and echo patterns. In order to obtain a sensible picture of the band structure, convective echoes at some distance from the plane should also be shown; however these usually do not then coincide with the water pattern obtained when they were penetrated at some later time.

As a compromise, in most cases, only those echoes are plotted which are close in time and location to the probe of a significant cloud formation. For example, in figure 4, for the west wall are plotted only those echoes at 1917 and 1948 GMT, approximately the times of the traverses through this wall. Similarly only the echoes for 1923 and 1942 GMT were plotted for the east wall. When the storm flights covered large areas, the radar cloud bands were well separated, and the band penetrations were widely scattered, all echoes appearing on the radarscope at a given time are shown. In these cases, the direction and speed of echo movement are given in the text so that it is possible to fit the water and echo patterns. However, it must be realized that none of the echo mappings duplicates the true cloud pattern at any given time. It is believed that they usually overestimate the coverage of the convective cloud systems.

Additional information as to cloud types and patterns was available from visual observations made by the Cloud Physicist and the Flight Meteorologist and from the cloud-particle samples obtained using the Foil Sampler. This instrument and the distributions of the samples collected in hurricanes are described in [4, 5]. For the present analysis the foil samples were used only to identify the character of the hydrometeors; i.e. solid or liquid.

For a semi-quantitative discussion of the gross areal array of the liquid water, the storms were divided into sectors and the frequency distribution of the water content values (1-sec. means)in each sector used as the statistic for comparison. In considering the variation of the water content with distance from the center of the storm, the total area covered was divided into 20-mi. wide concentric rings. Only measurements made outside the eye were included so that the innermost annulus was defined by the inner boundary of the wall cloud on the one side and the 20-mi. range on the other. This may bias the resulting distribution since the area so defined is largely filled with wall cloud which usually has relatively high water content. The possibility of this bias should be considered when comparing the distribution for the inner annulus with those for more distant rings.

The variation of water content with azimuth was studied in a gross manner by dividing the storm into quadrants, using the direction of motion as a basic reference. The division was made in two ways: one using the lines at ±45° from the direction of motion and the other using the direction of motion and its perpendicular (see fig. 2). The data were also divided into near and distant classifications, using the 60-mi. range line as the line of demarcation, in order to permit comparisons between storms. (Data are not available for ranges beyond this limit on all of the flights studied.)

A theoretical adiabatic liquid-water content has been computed for each flight and altitude. The calculations were made under the basic assumptions of parcel ascent from cloud base to measurement altitude with no dilution and no storage or loss of condensed water through settling or phase change (other than that implicit in a moist adiabatic process). The temperature and humidity soundings used were the August and September means for the West Indies published by Jordan [8]. Pressure height curves were determined from NHRP data printouts; estimates of cloud-base heights (the base of cumulus clouds was used) were obtained from Navy reconnaissance flights.

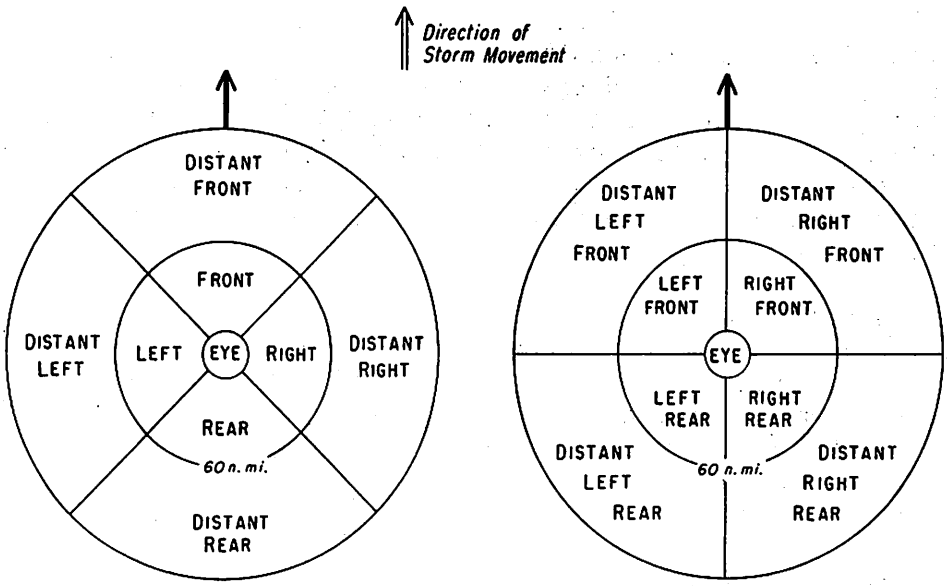


Figure 2. - Models used for the division of the storm area into quadrants.

It must be realized that the adiabatic water content is computed for highly idealized conditions and therefore may differ significantly from the true value. Where storage is significant, the water content may exceed the adiabatic; where entrainment is significant, when solid hydrometeors are present, and/or in layer clouds where cloud bases may be at much higher levels than that assumed, the computed water content may greatly overestimate true conditions. The computed water content remains a useful tool primarily in its role as a reference value. Deviations from this reference give an estimate of the degree to which the actual conditions differed from the assumed ones and are suitable for storm, altitude, and temporal comparisions.

The macro-features of the water distribution are discussed by storm in Section 3. Tabulations of the 1-sec. mean values of water content for all reduced records have been supplied to the National Hurricane Research Project Operations Base in Miami, Fla.

Representativeness of Measurements

The data must be interpreted with two considerations in mind: the characteristics of the measuring instrument and the general characteristics of the parameter being measured. The former is considered in detail elsewhere [2] for above-zero temperatures. At temperatures below zero, clouds may be composed of both solid and liquid particles; the paper-tape meter measures only the liquid portion of the mixture. In addition, in liquid-water clouds at temperatures below freezing, icing may occur around the sampling aperture, causing a decrease in the volume of air sampled. The instrument has no provision for monitoring icing or for measuring the air flow. Therefore when icing occurs, the calculated volume concentration underestimates the true density of the water. Because of compressional heating of the air in the vicinity of the sampler and frictional heating of the housing skin, icing probably is not a serious problem unless the ambient air temperature is more than a few degrees below zero.

The questions of representativeness arising from the areal extent of the hurricane system, the low areal density of the convective cores, and the transient nature (both in time and space) of the clouds are more difficult to evaluate. Since the data are collected from a single moving platform, the samples not only represent a very small fraction of the total population, but also include spatial and temporal variations. In interpreting any of the results it is necessary first to question the representativeness of the samples under consideration.

If, as suggested by Malkus et al. [11], there are preferred areas for the generation of large penetrative convective clouds and that the locations of these preferred areas remain relatively constant with respect to storm center, then direct comparison of measurements made in one storm sector with those made in another sector an hour or so later may be valid. However, until there is further proof that a persistence in the location of active convection does exist, such comparisons must be made with care.

It is felt that the samples obtained in traversing extensive storm sectors were sufficiently large and were collected in a sufficiently random manner for the frequency distributions to be fairly representative. Although the collections from two storm sectors may have been made an hour or two apart, other studies indicate that changes in the general flow patterns in the hurricane are so slow that the gross features of the areal distribution of water content probably do not change too much in the times considered. This however need not be true of the details of the distribution.

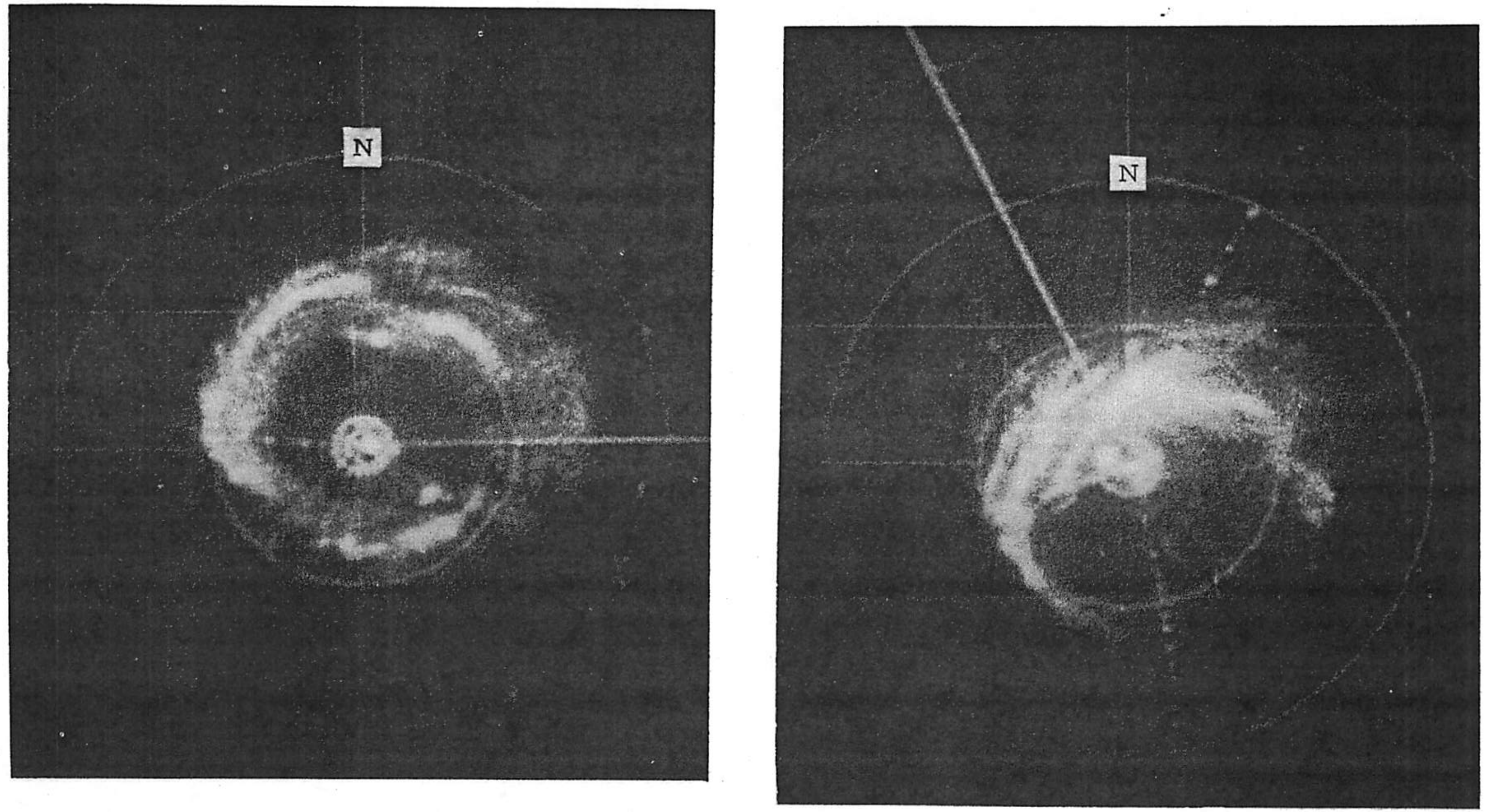
3. MACRO-FEATURES OF THE WATER DISTRIBUTION

Hurricane Carrie, 1957

Hurricane Carrie was one of the longest-lived hurricanes on record; hurricane-force winds were observed from September 7 to 17, 1957. The minimum surface pressure of 945 mb. occurred on September 12. The storm moved westward until the 12th, turned northward, and veered west-northwestward again on the 14th. Final recurvature to the east took place on September 16.

Water-content data are available for flight 70915B made by WB-50 No. 032 on September 15, 1957. At this time the storm was fully mature, with a central surface pressure of 960 mb. It was located at about 30°N., 57°W. and was moving on a course of 300° with a speed of about 12 kt. The cloud structure was composed of four or five convective bands, imbedded in continuous cloud decks occurring in several layers. At the flight level (18,000 ft.) the cloud decks were mainly altocumulus and altostratus and extended outward from the center to a distance of 120 mi.

The eye was about 40 mi. in diameter and was well defined, with cloud towers reaching to 38,000 ft. Although the eye appeared to be completely encircled by clouds, the radar observations indicate a non-uniform spatial distribution for the heavier rain areas (fig. 3). At least for the period of time that the wall clouds were within range of the airplane's radar, the cloud band outlining the west side of the eye was larger, more homogeneous, and greater in intensity than that on the east side of the eye. The band on the east side of the eye also seemed to have a shorter lifespan.



(a) (b)

Figure 3. - The radar echoes from the eye wall of hurricane Carrie, 1957 at (a) 1920 GMT and (b) 1946 GMT on Flight 70915B. Range markers: 20 n. mi.

Most of the flight was through extensive cloud decks; the weather reported was usually light rain, with occasional reports of light snow and convective clouds. The convective clouds are clearly manifested in the records as large increases in both the magnitude and the variability of the water content and in the airspeed fluctuations (an indicator of gustiness).

The airplane operated out of Bermuda, flew southeast to the storm, and made its penetration in the late afternoon. Shortly after the first eye penetration, there was an engine failure and the flight had to be terminated. However, a second eye penetration was made on the course adopted for return to base. The period covered in the analysis is quite short (from 1914 to 2000 GMT) - primarily because the recorder paper was depleted on the inbound leg some 80 mi. from center and was not replenished until the plane was within 20 mi. of the eye.

Due to an unusually high noise level in the measurements, uncertainties in the water-content measurements may be as much as 0.2 g./m.^{3} in some sections (particularly on the outbound leg). Although the high noise level may have been partly meteorological (high-frequency graininess in the continuous rain) the time coincidence between the onset of the engine trouble and a sizable increase in the noise level, suggests that it was due primarily to instability in the power supply. There also exists the possibility of residual moisture in the tape itself.

Although the flight was made above the freezing level, the free air temperatures were usually above -3°C., and it is felt that icing was negligible. However, there were reports of solid, as well as liquid, hydrometeors.

In figure 4 the average water content over "homogeneous" sections and the pertinent radar echoes are plotted along the path of the airplane, in the manner described in Section 2. In addition to the wall bands, there was a band of relatively heavy water concentration about 40 mi. to the west of the hurricane center and a band of convective echoes (not shown) at about the same distance east of the eye.

The distance over which high water-content values (averaging over 0.5 g./m.^{3}) extended was slightly greater in the western wall than in the eastern wall. This suggests that the wall band to the west of the center may have contained more water, though not necessarily in greater concentration. The maximum 1-sec. mean encountered on the first penetration of the west band was 2.40 g./m.^{3}, on the second penetration it was 1.16 (on this penetration the water content remained fairly high throughout); the maximum 1-sec. mean encountered on the first penetration of the east wall was 0.82 (this traverse was probably between cells of the band), on the second penetration it was 1.74 g./m.^{3} The water content values encountered in the band lying 40 mi. west of center were almost as large as those in the wall. Over the most concentrated portion the water content averaged 0.80 g./m.^{3} and reached a peak of 1.56 g./m.^{3}

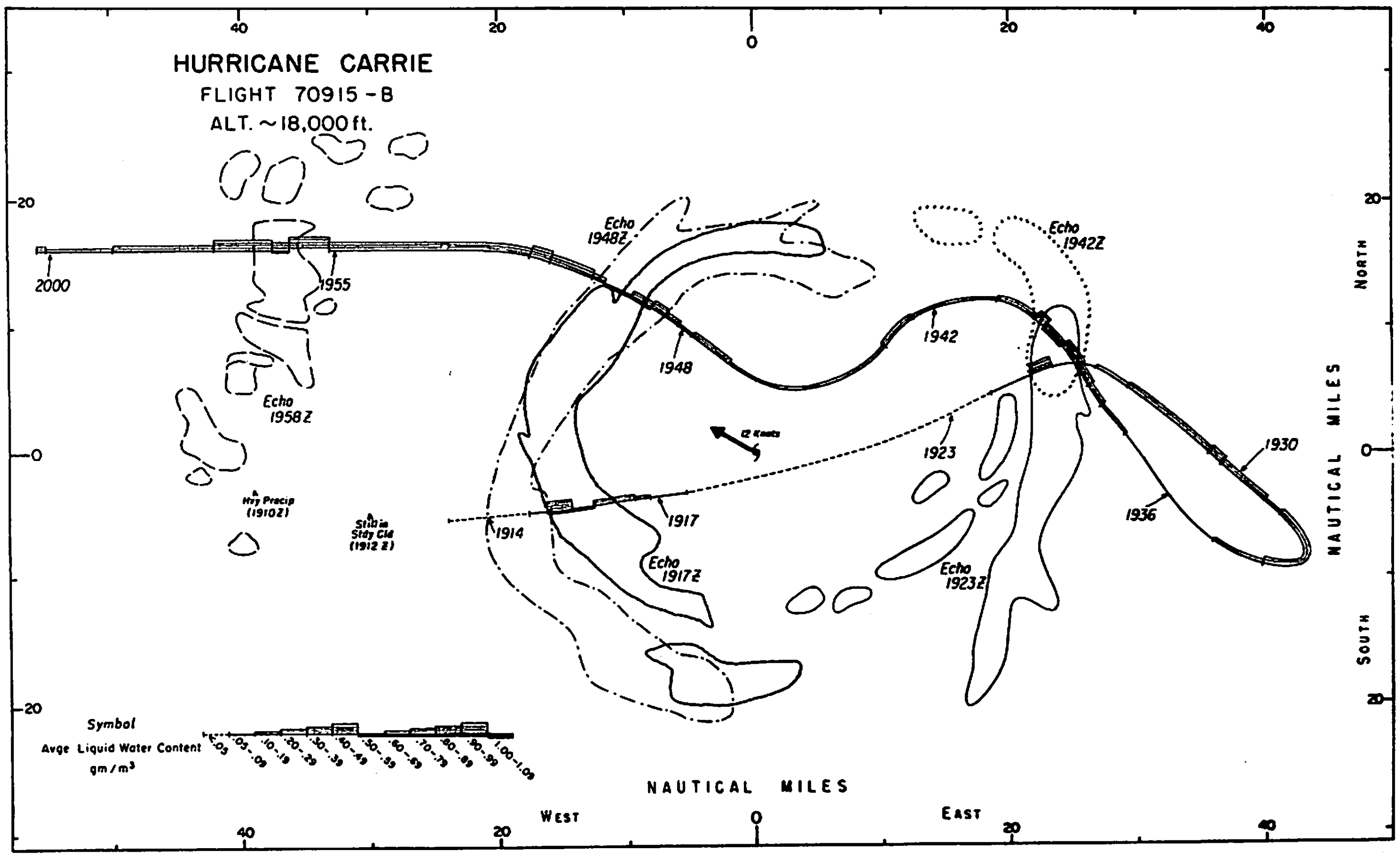


Figure 4. - Average water content over 'homogeneous' segments plotted along the flight path, and radar echoes in hurricane Carrie on September 25. Only partial radar presentation is shown for any specified time.

It is obvious from figure 4 that for long periods the airplane was in layer clouds with water content averaging 0.3 to 0.4 g./m.^{3} Calculations made on purely adiabatic considerations suggest that the bases of these layer clouds may have been about 1000 ft. below the flight altitude.

The theoretical adiabatic water content was 7.6 g./m.^{3}; observed water content never exceeded 2.8 g./m.^{3} Therefore even at maximum points the water content was less than 40 percent of that expected from purely adiabatic considerations. Diminishment of the liquid water is possible in many ways - dilution in the cloud, rainout, and, in this case, transfer of some of the liberated water into the solid phase.

Frequency distributions of measured water content (1-sec. means) are skewed to the right in figure 5. The majority of the area sampled had very low water content: water content values in excess of 0.5 g./m.^{3} occurred in about 5 percent of the area sampled; in only 1 percent of the area were they in excess of 1.0 g./m.^{3} In most of the storm area traversed, the water content values were less than 5 percent of the theoretical adiabatic value.

A comparison of the frequency distributions for the 20-mi.wide annular rings indicates a decrease in the incidence of the higher water content with range and also a consistent shift in modal values. The differences are most pronounced between the first and second annuli.

In figure 6 are shown the frequency distributions of water content (1-sec. means) for various quadrants of the storm. It can be seen that the water content tended to be higher in the forward portions of the storm than in the rear portions. There is a one-interval shift in the modal value between the front and rear quadrants, as well as much lower incidence of water content greater than 0.5 g./m.^{3} in the latter. Since the data for the left sector were collected entirely in the forward half of the storm but those for the right sector were collected in both rear and forward portions, comparable data are available only for right front and left front quadrants (fig. 6). A comparison of these suggests that the water content may have been somewhat greater on the right side of the storm (although individual high-water-content cores were observed on both sides).

Tropical Storm Becky, 1958

This storm was first noted on August 4, 1958, as an easterly wave lying at about 14°W. It moved rapidly west and west-northwest recurving on August 15 from a position of about 32°N., 75°W. Becky reached its most intense stage on August 12 with maximum winds of 60 to 70 kt. and minimum surface pressure of 1006 mb., and remained essentially unchanged for about 24 hours. Neither wind nor cloud field was well organized or particularly intense at any time.

The hurricane Project airplanes flew into the storm on August 13 and August 15. The water data collected by aircraft No. 032 on the former day have been analyzed. At the time of this flight (80813B) the storm was lo-

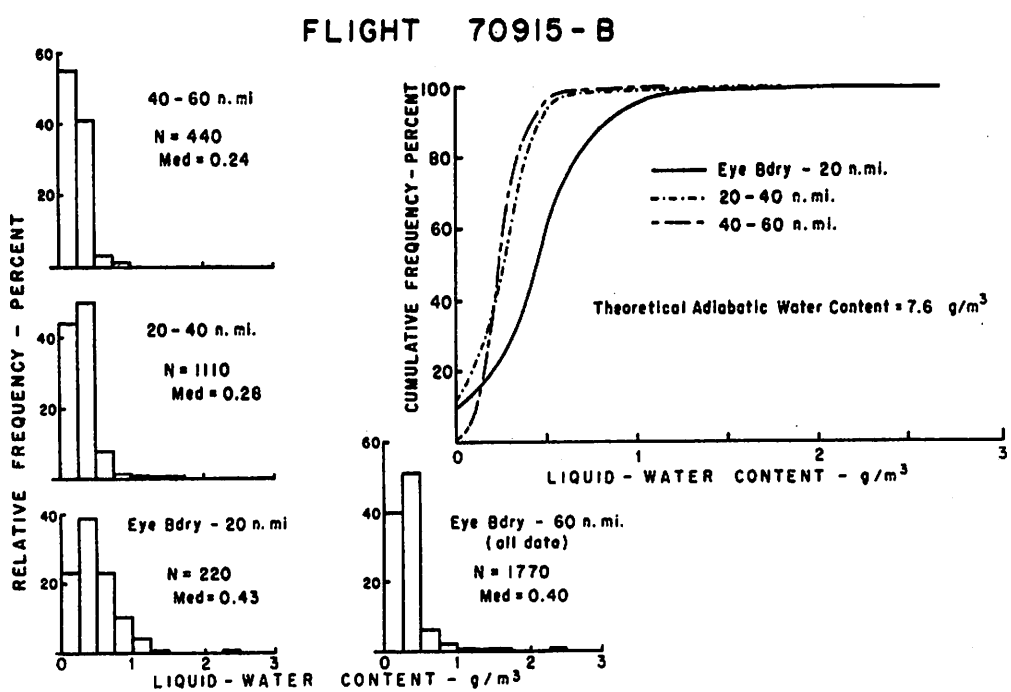


Figure 5. - Frequency distributions of water content (1-sec. means) for 20-mi. wide annular rings in hurricane Carrie.

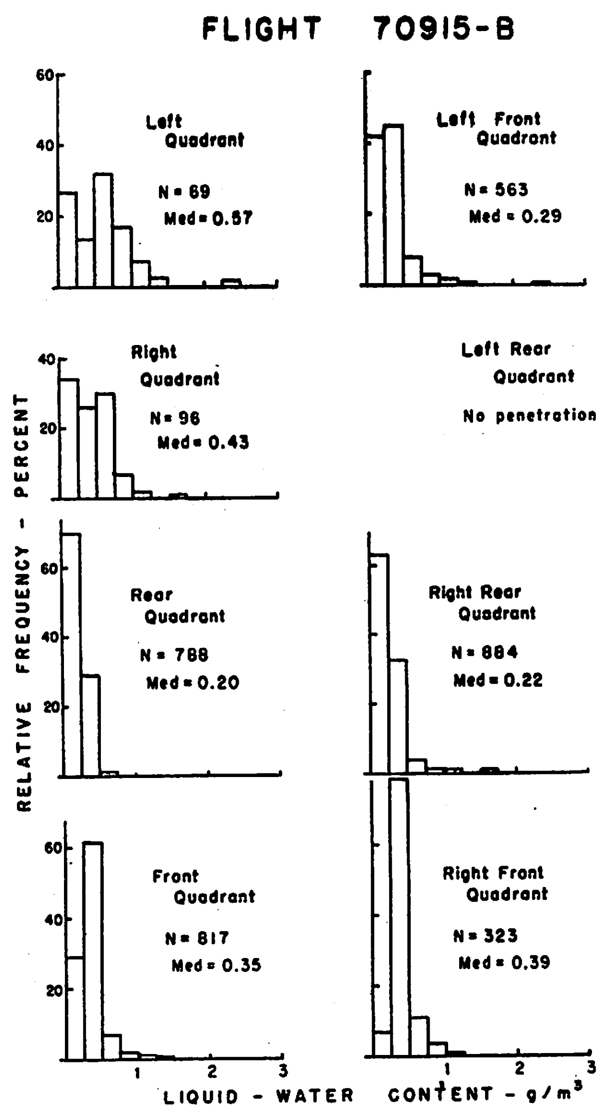


Figure 6. - Frequency distributions of water content (1-sec. means) in hurricane Carrie, by quadrant. Division into quadrants according to figure 2; all data were collected within 60 mi. of the storm center.

cated at approximately 21°N., 60°W. and was moving on a heading of 290° at 21 kt. The maximum winds were about 60 kt. and the central surface pressure was computed to be about 1006 mb. Although well-defined cloud lines were observed in the outer sections of the storm, particularly to the north, there was little organization near the center of circulation - and certainly nothing resembling an eye wall. Consequently, it was difficult to identify the center of the storm from the radar.

The wind circulation at the flight level (15,600 ft.) was diffuse and weak. The highest winds encountered by the airplane were about 30 kt. - in a cloud band almost 100 mi. north of the storm center. Penetrations were made into several cloud lines and on one or two occasions into stratiform decks extending out from the heavier portions of the lines. However, widespread cloud layers were not observed, and most of the time the airplane was flying through clear air.

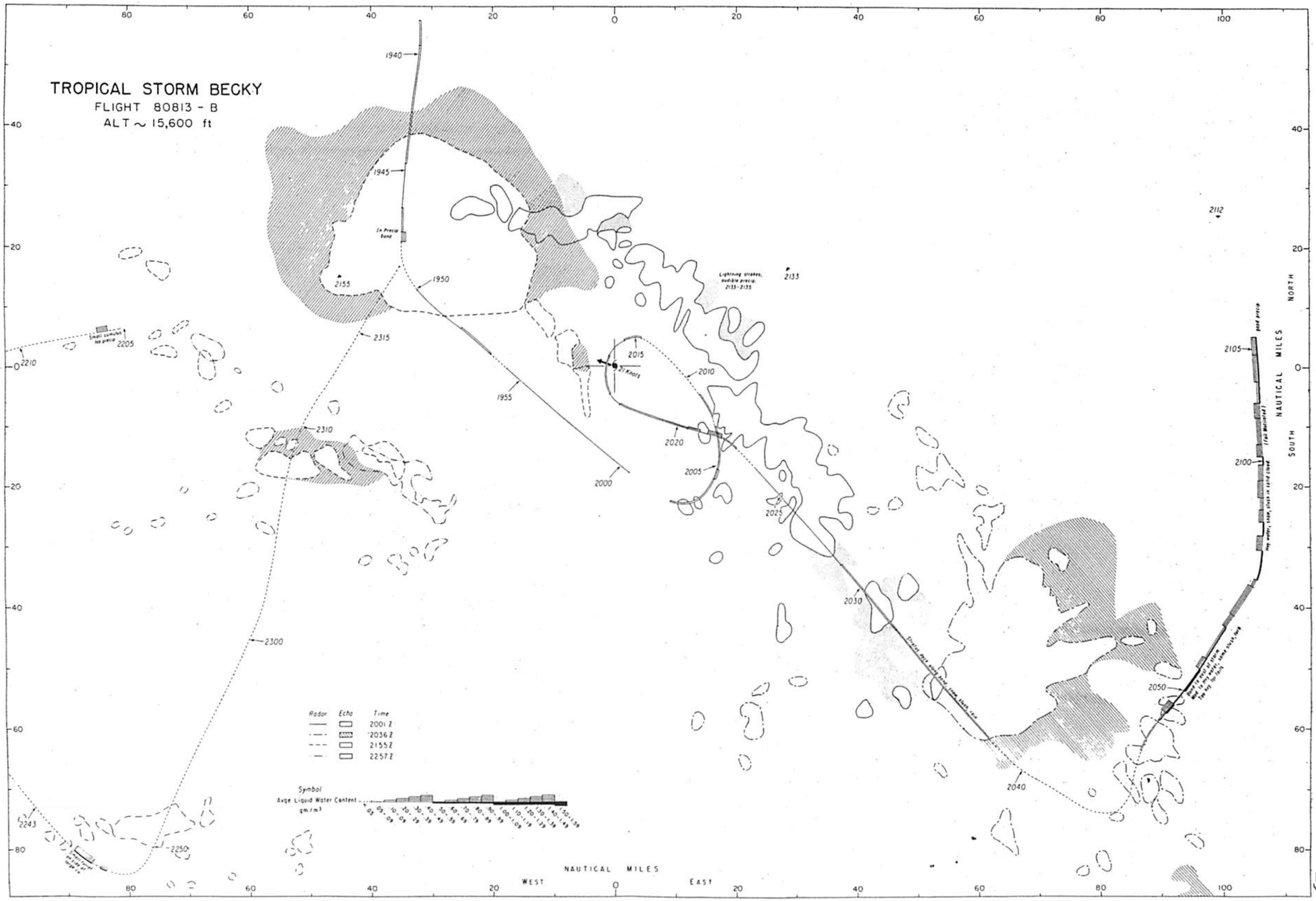
The flight covered a large area - extending from 140 mi. west of the center of the storm to about 100 mi. east, and from 80 mi. south to 100 mi. north. All available water content data were evaluated; unfortunately, the Heiland recorder lacked paper supply for about an hour right in the middle of the flight.

The pertinent equipment operated very well throughout the flight and the water-content measurements were very good. Although the flight was made in the vicinity of the freezing level, the air temperature was seldom below -3°C. and it is felt that icing of the water-content meter housing was negligible. However, the measurements refer to liquid water only - and solid hydrometeors were observed.

The average water content value over "homogeneous" segments, radar echoes, and observer comments are shown along the flight path in figure 7. The radar was operated with a maximum scope range of 60 mi. during most of the flight; the echo pattern shown for any specified time includes all echoes detected. Estimates of the direction and speed of the movement of the radar bands were obtained by tracking over consecutive 5- to 10—min. periods.

There were at least two, and possibly three, large convective bands in the area shown in figure 7 during the period of the storm penetration. However they were not in the area concurrently and there is, in fact, some question as to whether they all were in existence at the same time. Initially (2001 GMT echo) a long convective band extended for nearly 100 mi. from about 30 mi. northwest of the storm center curving around to the east and then to the southeast of the center. The echo detected at 2036 GMT probably was a

Figure 7. - Average water content over "homogeneous" segments plotted along flight path and radar echoes in tropical storm Becky on August 13. All echoes detected at the specified time are plotted; maximum radar range was 60 n. mi.


TROPICAL STORM BECKY
FLIGHT 80813 - B
ALT ~ 15,600 ft
NAUTICAL MILES
WEST
EAST
NORTH
SOUTH
1940
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Lightning strokes, audible precip. 2133-2135
Radar
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Time
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Symbol
Avge Liquid Water Content gm/m³

southern extension of this band, which either lay beyond the range of the radarscope at 2001 GMT or developed in the intervening time. The appearance of the radarscope at 2036 GMT suggests that there may have been cloud areas to the north and east which were not detected because of beam attenuation in heavy precipitation. This cloud band moved rapidly to the east-northeast (relative system), the band itself at 80 to 90 kt., the smaller outrider echoes at nearly 100 kt.

The extreme northwestern portion of the band was traversed perpendicularly at about 1948 GMT. The water content varied in a manner typical of cumulus clouds, reaching a maximum of about 0.65 g./m.^{3}, but averaging only slightly over 0.3 g./m.^{3} About half an hour later a small bi-cellular outrider cloud lying to the west of the band proper was penetrated. Again the water content measurements were typical of convective clouds - the average over the cloud as a whole was about 0.3, with a maximum 1-sec. mean of 1.05 g./m.^{3} There was no evidence of any but liquid hydrometeors on either of these penetrations.

The airplane skirted the western edge of the band as it continued southeast, entering the edge of a stratiform cloud that extended out westward from the southern end of the cloud band at about 2030 GMT. The water content measurements lay almost entirely between 0.1 and 0.2 g./m.^{3} and had the characteristics of stratiform clouds. However, the cloud physicist reported snow and slush during the period of the measurements and samples of cloud particles from the foil sampler verify the existence of both solid and liquid hydrometeors. Equivalent water content, computed from the foil samples, was about 0.3 g./m.^{3}

Measurements were obtained through much of the length of the band when it lay about 100 mi. to the east of the storm center. During this penetration, the radarscope was saturated for the first few miles, fading out gradually with range - obviously detection of more distant echoes was not possible because of the attenuation of the radar beam in the heavy precipitation area in the vicinity of the airplane. Very high water content was encountered, and again snow and slush were reported. The cloud particles were so large and numerous that the lead foils were mutilated on exposure. The most concentrated water content for the whole storm flight occurred in this area - averages of between 0.5 and 1.0 g./m.^{3} over distances of a few miles were not uncommon. Because of the existence of solid hydrometeors this is an underestimate of the total precipitation content. The largest values were encountered in the south - over a small section averaging nearly 1.5 g./m.^{3}, with a maximum 1-sec. mean of 2.27 g./m.^{3} The southern section of the band was more typically convective than that in the north, both in the character of the turbulence and in the cellular variation of the water content. The water-content measurements in the north exhibited a mixture of the characteristics for convective and layer-type clouds; there were no large cellular divisions, but shorter-period variations (less than 1000 ft. in length usually) were superimposed on a fairly constant, but high (0.5 to 1.0 g./m.^{3} usually) level of water content. The northern section of the band may have passed its peak and been precipitating out.

Unfortunately, there are very few data of a cloud physics nature for the time that the airplane flew west to the eastern limits shown in figure 7 - both the Heiland recorder and the radar camera lacked film supply. High values of water content, lightning, and turbulence were reported several times at about 2135 GMT, in the area lying between 10 and 30 mi. northeast of the storm center. A convective band must have been penetrated - one located to the west of that shown in the figure, which if it still existed, would have been located 50 to 100 mi. to the east.

The echo detected at 2155 GMT suggests the existence of a heavy rain band to the north and west of the center of the storm. A similar echo was detected in a position 20 to 30 mi. northeast of this one about an hour and a half later, as the airplane took up a course for home-base. No Heiland data are available for these segments of the flight.

The echo patterns shown in the southwest quadrant are fairly representative of the scattered cloud conditions that existed in this area at all times that it lay within the range of the airplane's radar. A large area to the west of that shown in figure 7 was also traversed (extending to 140 mi. west of storm center) but only a few isolated cumuli were observed.

The WNW - ESE line of well-spaced echoes detected at 2155 GMT, and also the similar one lying in about the same location an hour later, were somewhat more extensive and continuous at other times, but while in the range of the radar, never became solid bands. One of the small clouds in the first of these two lines was penetrated at about 2205 GMT. At this time it was composed entirely of water drops and had an average water contnet of about 0.45 g./m.^{3}, with a maximum 1-sec. mean of 0.90 g./m.^{3} The plane flew between clouds when passing through the second line.

A third line was located in the extreme southwestern corner of the area. On a penetration through two cells in the largest echo of this band the water content measurements averaged 0.99 and 0.71, with a maximum 1-sec. mean of 1.80 g./m.^{3} No solid hydrometeors were reported.

The theoretical adiabatic water content for the flight level was 7.14 g./m.^{3} In clouds in which both solid and liquid hydrometeors were detected, large deviations from this value are to be expected. However, even in the small, all-water cells, the water content values including the maximum points, were less than 40 percent of the theoretical value.

The predominance of low water content in the regions traversed by the airplane is evident from figures 8 and 9. The shapes of the frequency distributions are greatly influenced by the fact that a large portion of the storm penetration was through clear air. For this reason, the fraction of the traverse that was cloud-free is shown also. At least 45 percent of the total area traversed was clear of clouds. The incidence of water content values in excess of 0.5 g./m.^{3} was very low, indeed negligible, within 60 mi. of the center of the storm.

Comparison of the frequency distributions for successive annular rings

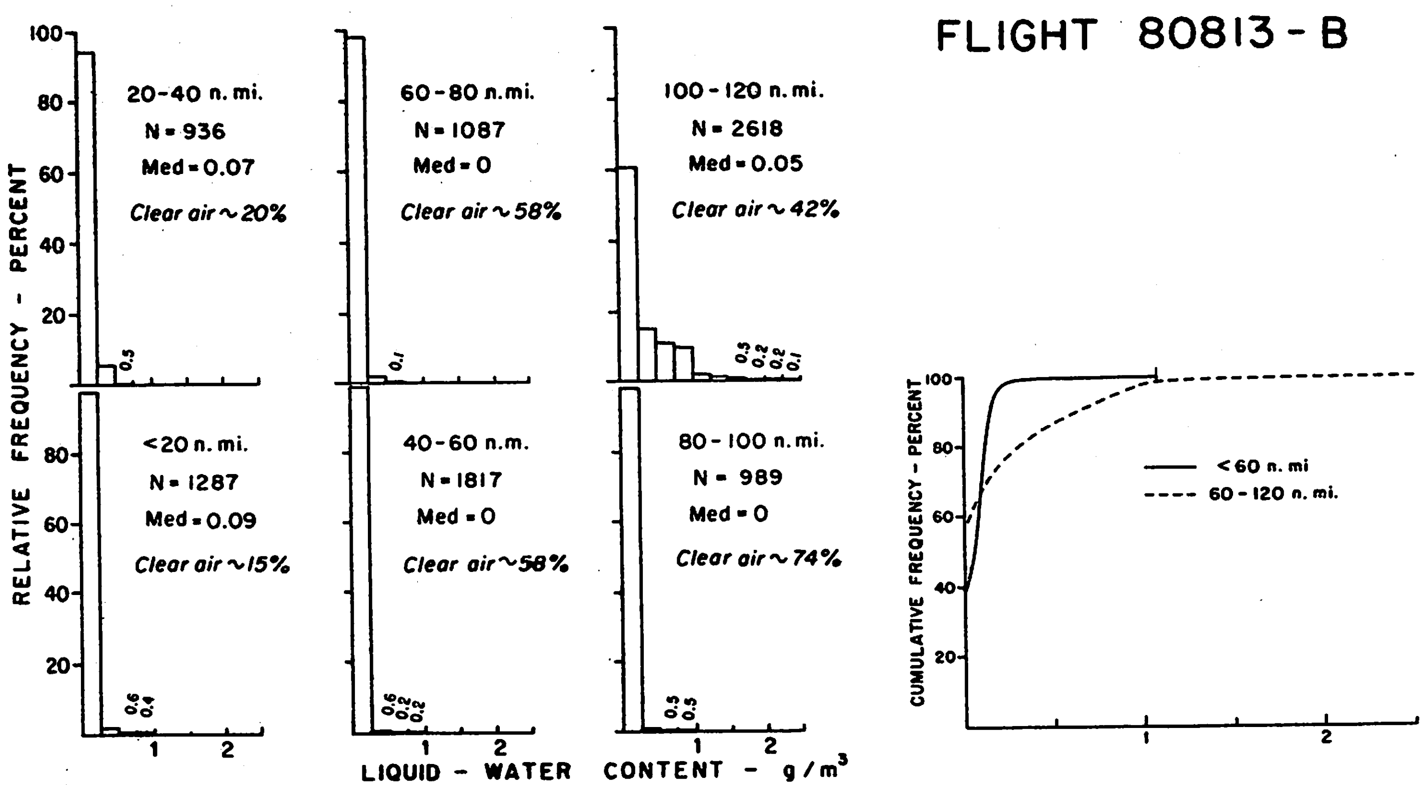

Figure 8. - Frequency distributions of water content (1-sec. means) for 20-mi. wide annular rings in tropical storm Becky.

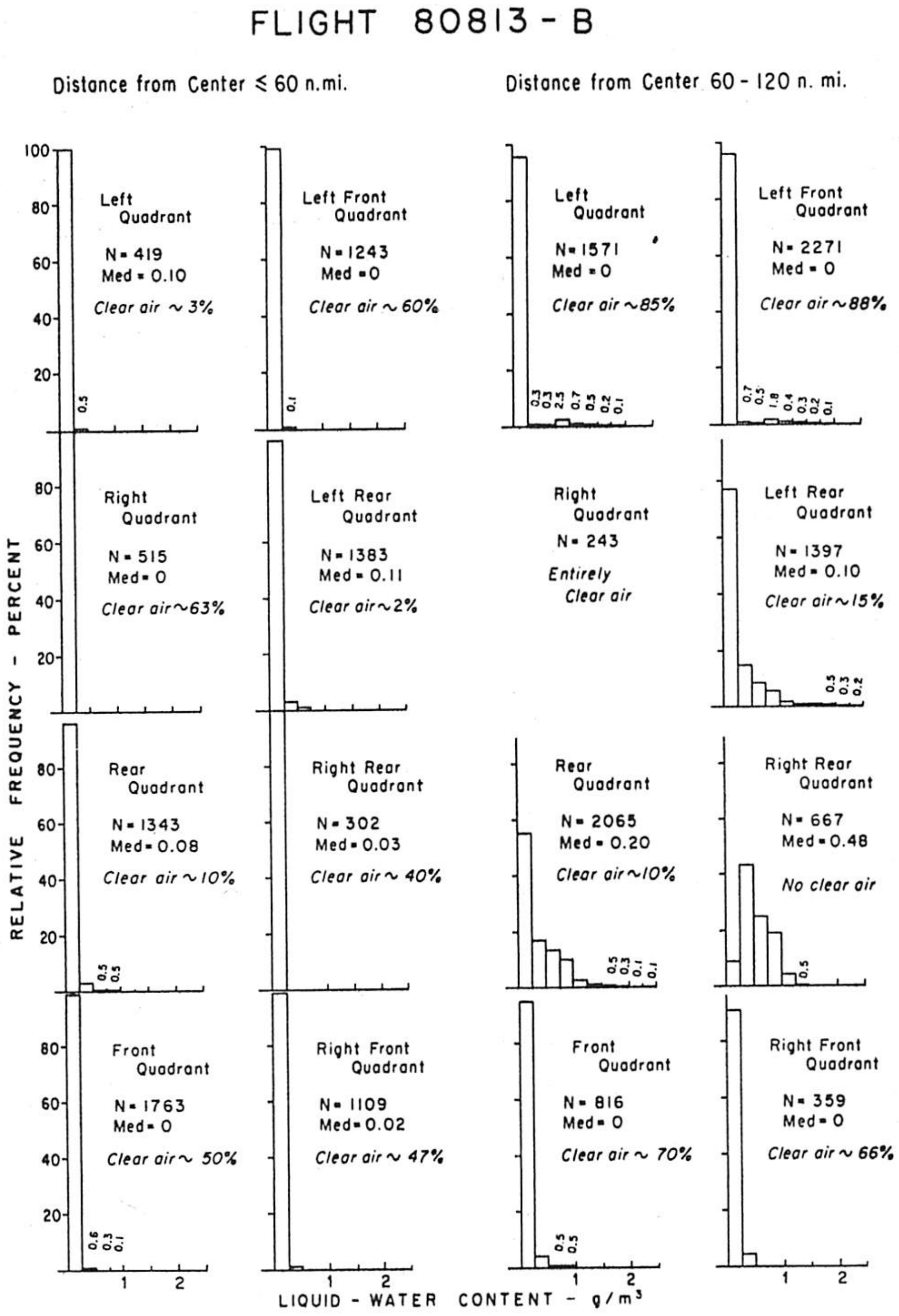

Figure 9. - Frequency distributions of water content (1-sec. means) in tropical storm Becky, by quadrant. Division into sectors according to figure 2.

within 100 mi. of center (fig. 8) suggests a slight decrease in water content with range; this trend is completely refuted by the measurements for the 100 to 120 mi. annulus in which exceptionally heavy concentrations of water were encountered. The high values for water contents in the area were collected almost entirely during the longitudinal traverse through the long convective band shown much closer to the storm center in figure 7, but the heart of which was not penetrated until it lay far to the east. There does, however, seem to be a consistent tendency for the amount of clear air to increase with range.

The distribution of water in the various quadrants is shown in figure 9. There was relatively little difference between quadrants (within 60 mi. of storm center) except that the incidence of cloud-free air was much lower in the left-rear quadrant than in the others. Between 60 and 120 mi. from the storm center, the water content tended to be much higher and the incidence of cloud-free air much lower in the rear than in the forward parts of the storm. However, as in the case of the 100-120 mi. annulus, this was due primarily to the longitudinal traverse of a single band.

Hurricane Daisy, 1958

Hurricane Daisy began as a small cyclonic system, which, on August 23, 1958, broke off from a stagnating wave located at 20°N., 75°W. Intensification began on the evening of the 24th and proceeded rapidly. The winds reached hurricane force early on the 25th and continued increasing in strength as the storm deepened — to in excess of 100 kt. at the height of the storm. The storm moved toward the northwest and west-northwest at 7 or 8 kt., recurving toward the northeast around midday on the 26th. The lowest surface pressure (948 mb.) occurred late on the evening of the 27th.

The clouds occurred in several layers. Navy reconnaissance reported cumuliform clouds covering 4/8 to 6/8 of the sky: small cumuli with tops at 6000 ft., occasional patches of bulging cumuli reaching 10,000 to 15,000 ft., and scattered areas of cumulonimbus clouds with tops at 20,000 and 30,000 ft. Layers of altostratus clouds at 10,000-12,000 ft. and an overcast of cirrus or cirrostratus at 30,000 ft. were reported through most of the storm region.

The radar echo configuration, which was well defined for the period of the 25th through the 27th, was elongated in a roughly NNW-SSE direction (figs. 10, 11). The radar eye had a diameter of 15 to 20 mi. on the 25th, and was partially open on the west for most of the flight period. It was even smaller (diameter of about 10 mi.) on the 27th and usually closed. The wall cloud extended to 40,000 ft. There was severe weather in all quadrants close to the center of the storm, but the severest weather, at least during the period of intensification, was reported in the southeast quadrant.

The NHRP airplanes flew eight missions into hurricane Daisy. An exhaustive description of the data collected and the analyses made by the Hurricane Project staff in Miami has been published by Colón [6]. In addition, special characteristics of the storm have been studied by others [9, 10, 11, 12]. The water content data are described herein as a supplement to these studies. Data are available for only two flights - one on the 25th and the other on the 27th.

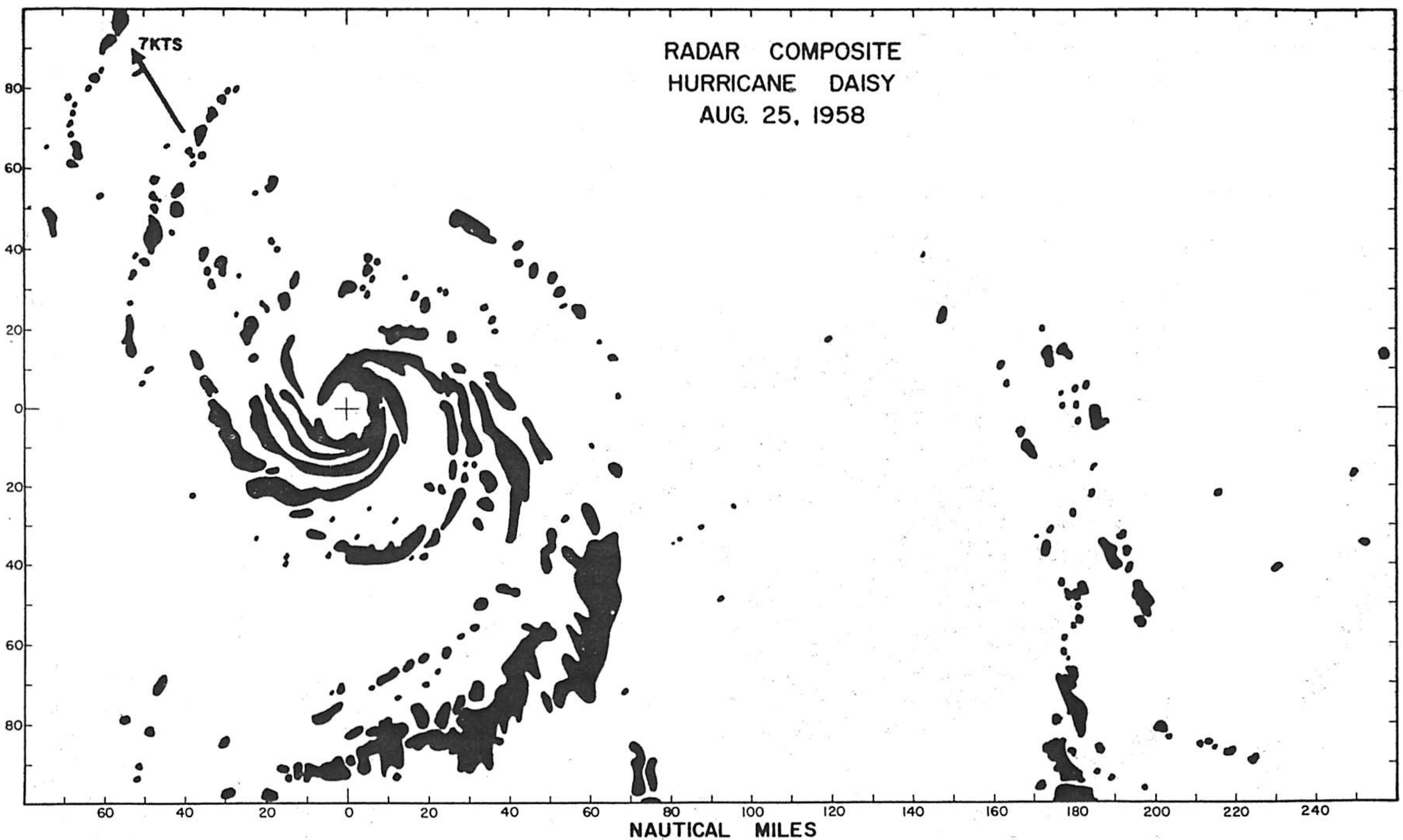

Figure 10. - Radar composite of hurricane Daisy on August 25 from radar film obtained on flight'80825-C (altitude 35,000 ft.). Prepared by staff of the National Hurricane Research Project Operations Base.

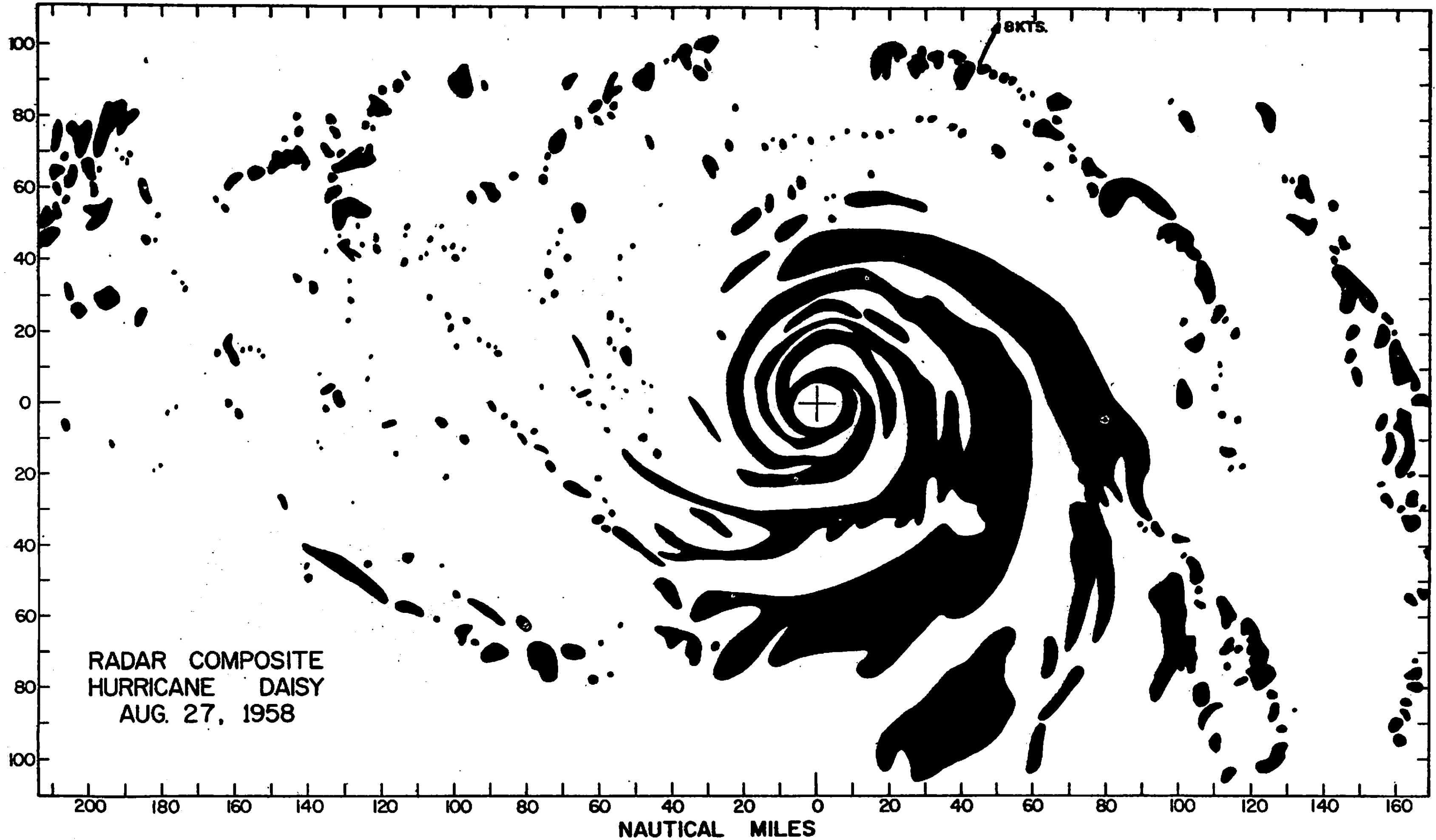

Figure 11. - Radar composite of hurricane Daisy on August 27 from film obtained on Flight 80825-B (altitude 13,000 ft.). Prepared by staff of the National Hurricane Research Project Operations Base.

Flight 80825B. - This flight was made at about 15,600 ft. between 2000 GMT on August 25 and 0230 GMT on August 26th. The central surface pressure at this time was 992 mb. and falling rapidly. The storm was moving north-northwestward at about 7 kt. One of the objectives of this mission was a seeding experiment [3]. In connection with this experiment, extensive maneuvers were executed in the northeast quadrant of the storm. The remainder of the flight followed a cloverleaf pattern.

Water content data are available for most of the period from 2053 to 0115 GMT: the major breaks in continuity occurred from 2136 to 2226 GMT while the northeast quadrant was under surveillance, with another 15-min. break occurring on one of the traverses through the southeast quadrant. The cloud physics data are of good quality. Although the flight was made above the freezing level the free-air temperatures were generally warmer than -3°C. and icing of the water-content-meter housing was probably negligible. However, mixed hydrometeors were observed and collected with the foil sampler in many parts of the storm and it must be recognized that the measurements in these sectors refer only to the liquid portion of the cloud mass.

In figure 12 are shown the water content data along the flight path, and descriptions of clouds and hydrometeors culled from observers' reports and foil samples. Also shown are echo patterns for a sequence of observations close to the middle of the observational period. The radarscope had maximum range of 20 mi. for most of the flight; the radar coverage for the times noted in the figure was extended by using 'scope pictures covering several minutes. The locations of echoes which were out of range at the specified time were adjusted using the direction and speed of motion of the echoes as determined from a sequence of pictures. Since the flight covered several hours, there were radar data available at intervals of 1/2 to 1 hour for several parts of the storm. In some locations there were significant changes in the echo patterns between the observations. These will be discussed below in connection with the water measurements. However the sequence shown in figure 12 gives a fair representation of the conditions met in the storm.

It may be seen from figure 12, that the convective bands and the high water content values tended to be concentrated in the eastern half of the storm. During the time that it was under suveillance, only the three convective bands shown (plus a fourth small one just beyond the southwestern-most excursion of the aircraft) were detected in the whole western half of the storm beyond 20 mi. from center. (The area within 20 mi. is considered part of the wall structure and is discussed below.) Other than these bands, only clear air or thin altostratus were encountered.

The two bands in the northwest quadrant were composed of relatively small, well-separated echoes. The individual units moved S or SSW at 65 to 70 kt.; the bands as a whole had a counterclockwise rotation. The clouds penetrated in these bands were composed entirely of liquid hydrometeors at the flight level, with water content averaging 0.4 to 0.6 g./m.^{3} The highest water-content measurements were about 1 g./m.^{3}

The band shown in the southwest quadrant (0042 GMT) may have been one detected and penetrated nearly an hour earlier in the northwest. (Because of

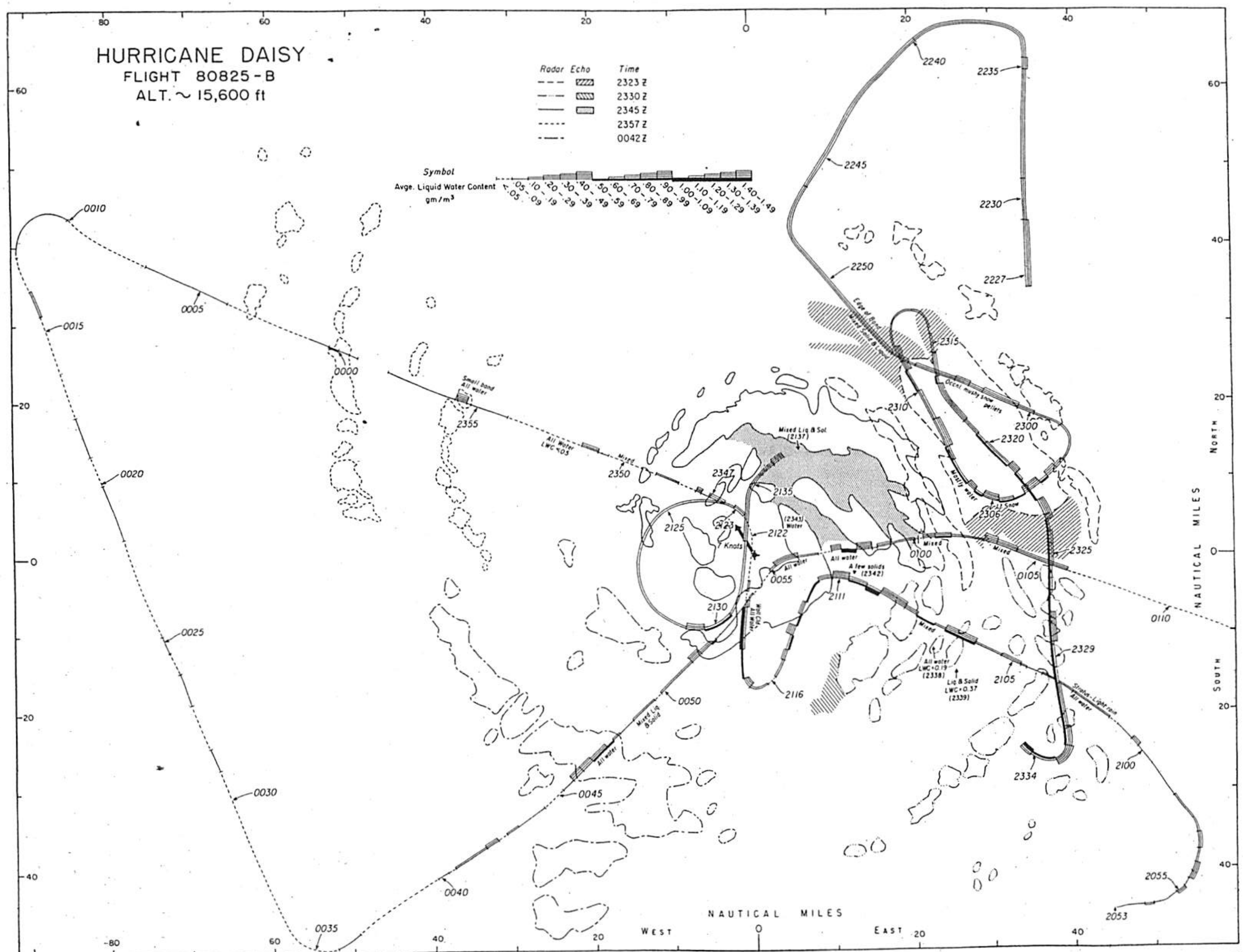

Figure 12. - Average water content over "homogeneous" segments plotted along flight path and radar echoes in hurricane Daisy on August 25. Partial composite of radar film (see text).

the short radar range, the bands can be tracked for only relatively short periods.) However, it is more likely that it is a third band that was just beyond the range of the radar earlier, or one that developed in the intervening time. The motion of the band was roughly counterclockwise relative to the center, with individual echoes having speeds of about 35 kt. Although mixed hydrometeors were observed in the thin stratiform shelf which extended to the north of the band, foil sample collections and observer comments indicate that the main portion of the band was composed entirely of water. There were several contiguous cells in the 4-mi. segment comprising the most active part of the band. The average water content in this area was about 0.7 g./m.^{3} and the highest water content was 2.19 g./m.^{3} Both the average water content for individual cells and the peak values were higher in the southwest quadrant than in the northwest.

The eastern half of the storm had a much higher density of convective bands, which were also larger, more continuous, and usually wetter than those in the western half of the storm. The series of three NW-SE traverses through the band lying about 35 mi. northeast of the center were in connection with the seeding experiment, which has been discussed by Braham [3]. Since the airplane was in heavy cloud most of the time, it is difficult to establish continuity from the radar. Although it is doubtful that the two later passes were through the portion of the band that was seeded (the AgI burner was on from 2235 to 2305 GMT), all three were through heavy portions of a cloud band located in the general area. An examination of the water content measurements shows that the apparently homogeneous cloud was in fact composed of many hard cores of high water content separated by areas of lesser intensity.

Even at the time of the first traverse (the easternmost of the three) mixed hydrometeors and light snow were encountered. The water cells were small in lateral extent - seldom more than half a mile in length. The water content in most of the individual cells reached peak values of more than 0.7 g./m.^{3} (1.62 g./m.^{3} was the highest) but averaged less than 0.35 g./m.^{3}

The water content values on the second and third passes (to the west of the first), were higher. They always exceeded 0.25 g./m.^{3} and averages over homogeneous segments ranged up to 0.75 g./m.^{3} The cell dimensions were greater than they had been earlier - most were between 1 and 1-1/2 mi. in length. Most cells had peak water content over 1 g./m.^{3}: the highest water content encountered on the second pass was 2.91 g./m.^{3}; the highest on the third was 3.33 g./m.^{3}

This same band extended into the southeast quadrant of the storm. The water content was consistently high in the southern extension but the measurements obtained in its southern extremity had many of the characteristics of stratiform clouds: the water content maintained a fairly constant level on which were superimposed short-period variations. However the level of the water content through this section (0.5 to 0.75 g./m.^{3}) was much more characteristic of convective than of stratiform developments. This area was probed also at the beginning of the storm penetration some 2-1/2 hours earlier (2100 GMT). At that time stratus and light rain were reported, with water content averaging only 0.2 to 0.3g./m.^{3}

Two radial traverses (both inward toward the eye) were made through the southeast quadrant - one starting at about 2100 GMT, the other at about 2330 GMT. The stratus and light rain mentioned above were encountered on the earlier of these. Convective clouds imbedded in this stratiform layer were penetrated close to the center. In at least one of these cumuliform clouds some solid particles were collected. The convective cells were clearly defined and were between 2 and 3 mi. in diameter. The two most active bands were located at 23 and 30 mi. east of the center of the storm. The latter was the more intense, as indicated by the magnitude of the water and of the turbulence; the water content averaged 0.82 g./m.^{3} while the peak value was 3.10 g./m.^{3} The water content in the former averaged 0.55 g./m.^{3} and had a peak value of 0.9 g./m.^{3} Unfortunately, the Heiland recorder did not have a paper supply on the second pass so that no quantitative water-content data are available. However, from comments made by the cloud physicist and from foil collections it is obvious that heavy convective cloud areas were traversed - some of which were composed of mixed hydrometeors, some of which were entirely water.

The eye and its "wall" were penetrated three times on this flight: first, at about 2120 GMT when an entire circuit was made; second, at about 2340 GMT on a WNW heading slightly to the north of the center; the third time at 0050 GMT on a NE and E heading to the south and east of the center. A comparison of the echo structures around the eye at the approximate times of these penetrations (fig. 13) indicates significant temporal changes. These were caused by cloud movement, new development, and dissipation. Only the former can be estimated with any degree of confidence. The wall and adjacent bands were rotating around the center very rapidly - at nearly 100 kt. for some of the features in the outer bands and more rapidly for some of the features along the inner wall [9]. Therefore water-content measurements made at different times in the same location relative to storm center were not from the same cloud area.

Despite the obvious changes, the wall seemed to maintain the same general character. It was composed of two or three bands which tended to be broader and more closely spaced on the east than on the west. Periodically the west side tended to "open" so that the eye was delineated by a group of small echoes rather than by a continuous cloud band.

The greatest water content in the vicinity of the eye was encountered in the south wall early in the flight (about 2118 GMT). It averaged 1.10 g./m.^{3} over a distance of about 6 miles, with a peak value of 4.23 g./m.^{3} The water content exceeded 2.50 g./m.^{3} over distances of about 1/4 mi. in half a dozen sections spaced at intervals of about 3/4 mi. No solid particles were collected or reported in these clouds. This wall was also penetrated about 12 min. later, and again at about 0053 GMT (third pass). Both of these traverses

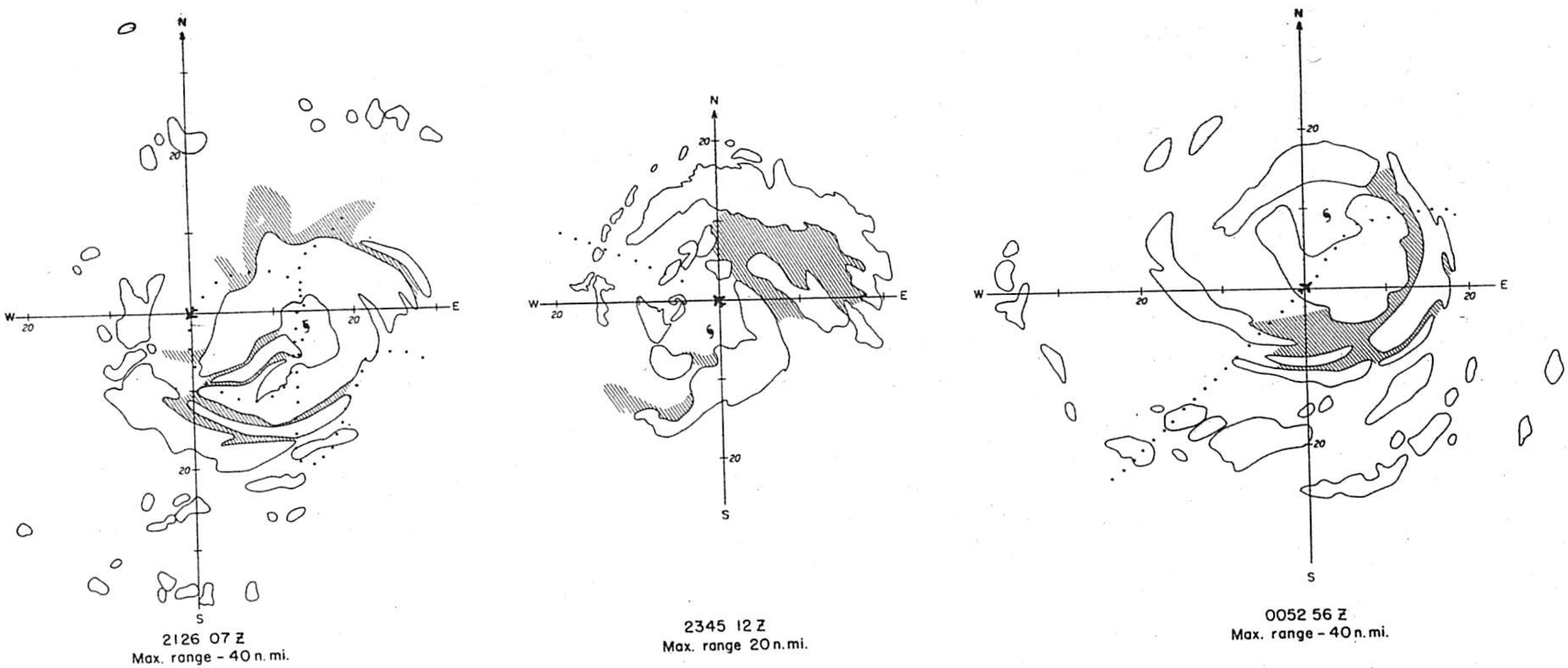

Figure 13. - Radar configuration of clouds near the center of the storm at the times of the eye and eye-wall penetrations in hurricane Daisy on August 25.

were through narrow or broken parts of the wall and the water content was much lower - averaging less than 0.7 g./m.^{3} in the convective portions.

High water-content values were also encountered in the outer portions of the east wall (12 to 14 mi. from the storm center), in an area which was traversed three times during the flight. In the heaviest cloud sections, the water content averaged 1.65 g./m.^{3} on the first penetration at about 2110 GMT and 1.05 g./m.^{3} on the third penetration nearly 4 hours later. Peak values in excess of 3 g./m.^{3} were measured on both traverses. Only liquid hydrometeors were reported on these probes - but a few solid particles were collected around 2340 GMT on the second penetration through the same area. (No Heiland record, and therefore no quantitative water content data, are available for this traverse.)

The outer bands of the southeast wall had moderate water content values, averaging 0.5 to 0.7 g./m.^{3} over the heavier cloud segments. The cellular structure in this area was mainly that of small rain cells (1/4 to 1/2 mi. in diameter).

The measurements obtained in the north and west walls indicate that the clouds there were mainly stratiform in nature with perhaps a few scattered buildups. The water content was generally low, averaging less than 0.3 g./m.^{3} even in the thicker sections. Solid hydrometeors were detected just to the north of the center in the interstitial stratiform cloud. The probes to the west of the eye were also in thin cloud - perhaps between bands on the first probe, probably through broken sections on the second.

As is obvious both from figure 12 and from the description above, the eastern side of the storm had much more water than did the western. From the frequency distributions of water content measured in various quadrants of the storm (fig. 14), it can be seen that, in the relative coordinate system, the cloud water was most heavily concentrated in the rear quadrants, with the greatest concentration in the right rear quadrant.

The frequency distributions of the water content measured in 20-mi. wide annular rings (fig. 15) indicate a decrease of water content with distance from the storm center. There is not too much difference between the two innermost rings (except that water content in excess of 2.25 g./m.^{3} was not found beyond 20 mi.); the pronounced decrease begins beyond 40 mi. with a sharp drop in the frequency of water content values between 0.25 and 2.25 g./m.^{3} between the second and the third annular rings. This decrease becomes even more marked beyond 60 mi. where values of over 0.5 g./m.^{3} were almost never encountered.

As in the two storms discussed above, the measured water content was much lower than would be expected from purely adiabatic considerations. The calculated adiabatic water content was 7.3 g./m.^{3}; the highest water content

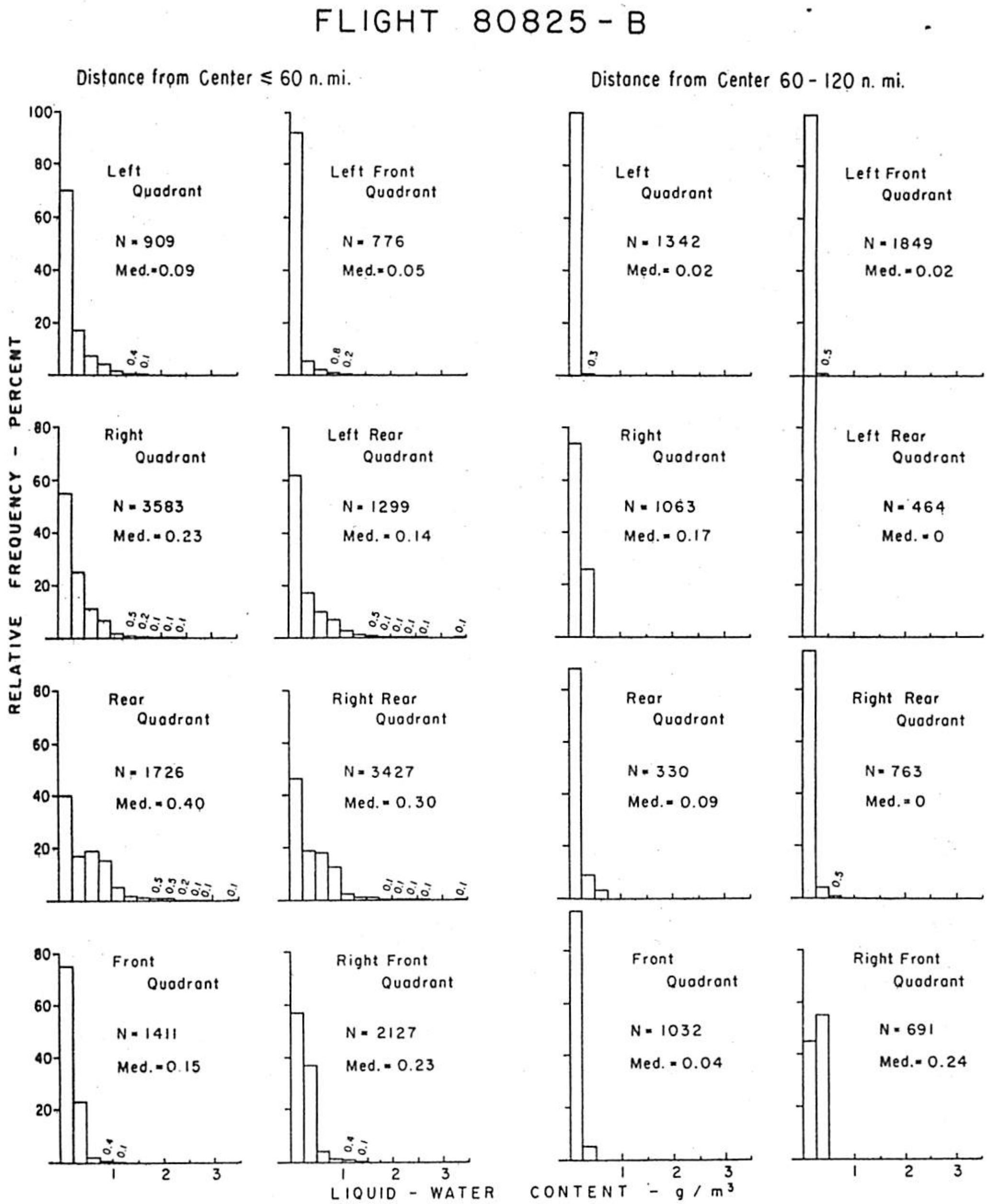

Figure 14. - Frequency distributions of water content (1-sec. means) in hurricane Daisy on August 25, by quadrants. Division into sectors according to figure 2.

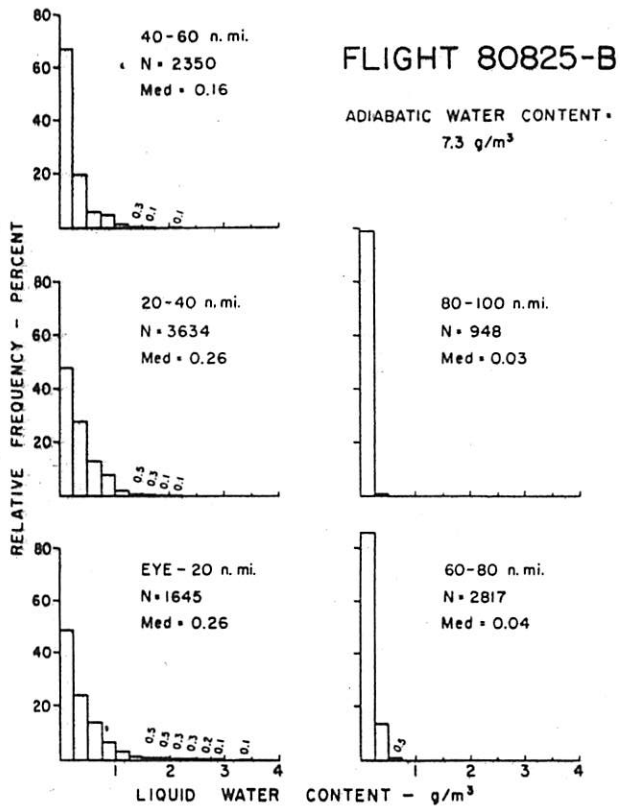

Figure 15. - Frequency distributions of water content (1-sec. means) for 20-mi. wide annular rings in hurricane Daisy on August 25.

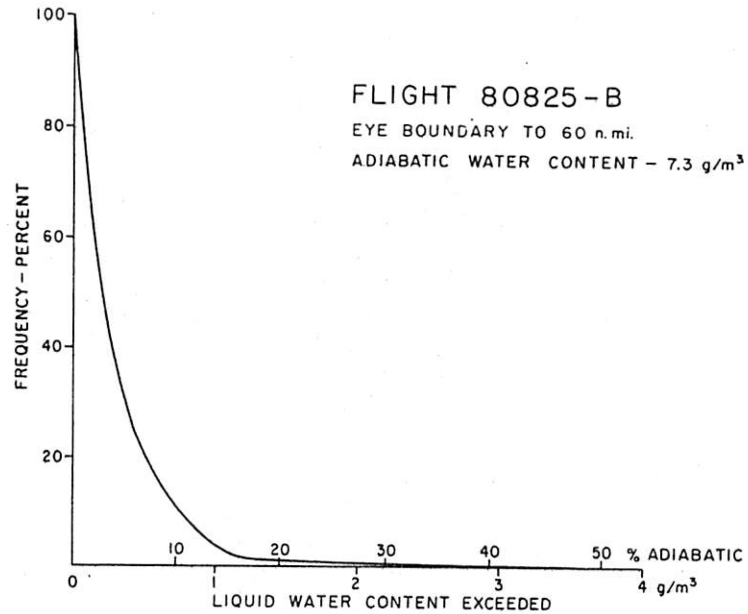

Figure 16. - Percentage of observed water content measurements which exceeded specified amount, hurricane Daisy, August 25.

measured during several hours of flight time was 4.23 g./m.^{3} (58 percent of the theoretical value) while the highest 1-sec. mean was 3.60 g./m.^{3}, less than 50 percent of the theoretical. From figure 16 it can be seen that less than 5 percent of the traversed area had water content in excess of .1 g./m.^{3} On about 9/10 of the flight path the water content values were less than 10 percent of the adiabatic. In some of these areas the low water content (relative to the theoretical adiabatic) was due, at least in part, to the fact that some of the condensed water was in the form of ice; in other areas the clouds were stratiform in nature with bases 1000 to 2000 ft. below the airplane, rather than many thousands as assumed in the adiabatic calculation. Where the clouds were unquestionably convective in nature, and where there was no evidence of the ice phase, the depletion must have been through rain-out and dilution by mixing.

Flight 80827B. - This flight was made at an altitude of about 13,000 ft. between 1500 and 2200 GMT on August 27. The surface pressure at the time of the flight was 950 mb. and still falling; the lowest surface pressure (948 mb.) was reached a few hours later. The storm was moving in a direction of 25° at a speed of 8 kt. The winds were very strong - up to 116 kt. at flight level.

The cloud structure seen by radar (fig. 11) was similar to that on the 25th but somewhat more extensive. The eye was only 12 mi. in diameter and occasionally open on the west. The wall clouds reached to 50,000 ft. The cloud distribution was again asymmetrical - the bands were much heavier and more extensive on the east than on the west. Also, high winds extended out to much greater distances on the east than on the west.

The flight was made below the freezing level (temperatures between +5° and +10° C.) so that there were no icing problems. Solid hydrometeors were reported only in the eastern wall so that the water content data are highly reliable albeit short in duration. Extremely high water content was encountered on the first pass through the storm, so high that the measuring tape was saturated, causing it to tear. Since it was not possible to reload the tape spool in flight, no additional water content data could be collected. Therefore data are available only for a radial penetration of the southwest quadrant and a small portion of the eastern and southeastern walls.

The airplane penetrated three major band systems (fig. 17); one lying about 100 mi. from center, one about 50 mi. from center, and the wall cloud and its associated bands within 20 mi. from center. Very heavy concentrations of water were encountered in all of these bands; however, there were unusually clear or low water conditions between them. Stratiform and scuddy cloud matter in the interstitial area was very thin or non-existent.

The outermost band extended for about 100 mi. - well beyond the area shown in figure 17. The individual echoes in the band were moving E or ENE at 20 to 25 kt., more slowly than the winds, and with a strong component inward toward the center of the storm. Only one of the clouds in the band was probed. It was composed of four major cells with three or four minor ones on the periphery. Very large water content values were encountered; averaging

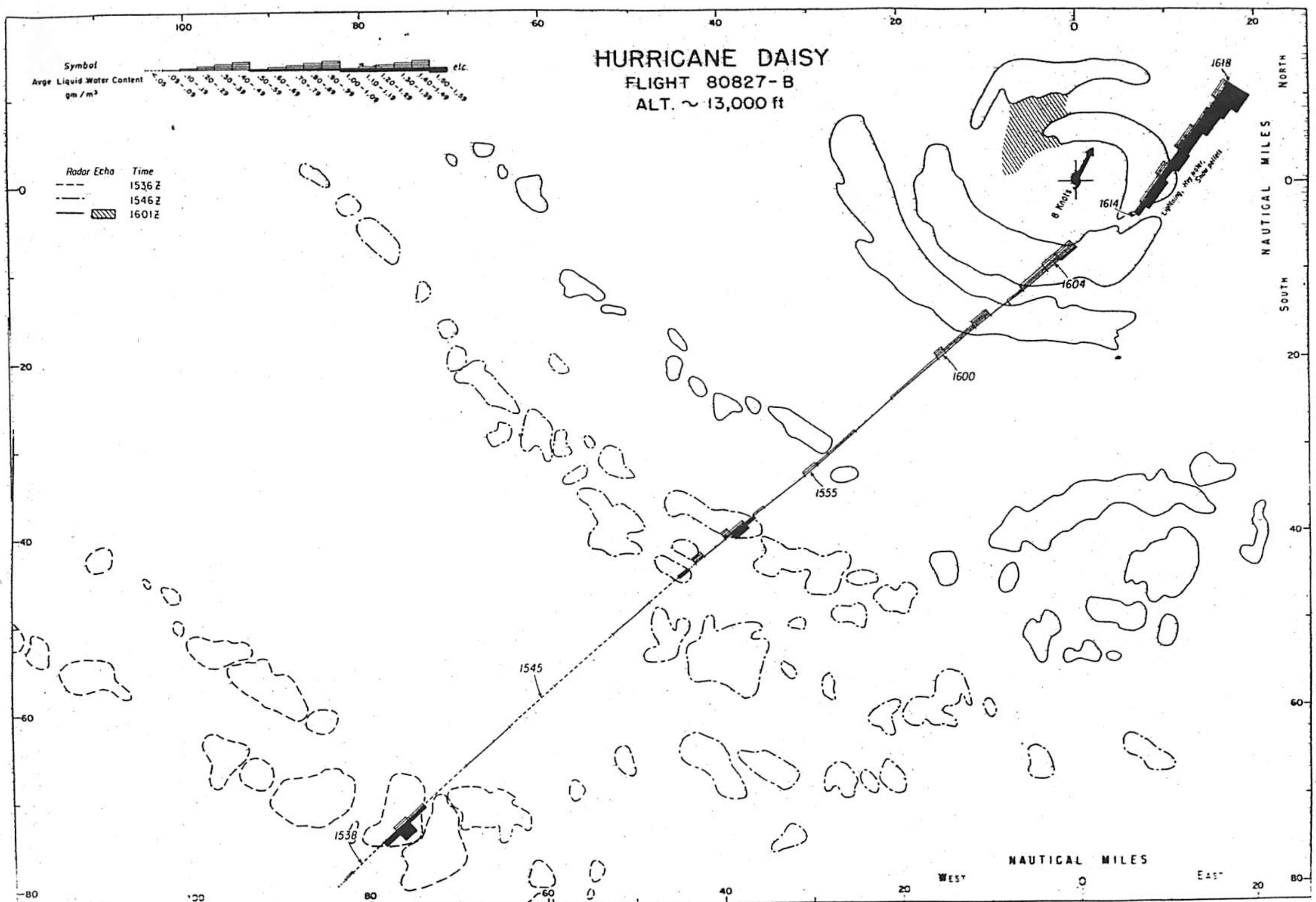

Figure 17. - Average water content over "homogeneous" segments plotted along the flight path, and radar echoes for hurricane Daisy on August 27. Only partial radar presentation is shown for any specified time.

4.25 g./m.^{3} over the most intense cloud segment (nearly 2 mi. in length) and 2.25 across the entire 6-mi. width of the cloud. The highest 1-sec. mean water content was 8.03 g./m.^{3}, over 20 percent more than the adiabatic water content (6.52 g./m.^{3}).

Several clouds of the band located at 50 mi. from the storm center were penetrated. The average water content varied considerably - from about 0.25 g./m.^{3} in the thinnest cloud to a little over 1 g./m.^{3} in the most intense. The highest average for a 1-sec. period was 4.69 g./m.^{3}, about 70 percent of the adiabatic value. The individual echoes in this band were moving at about 20 kt., roughly half the speed of the winds. Most had a component of motion inward toward the storm center, but it was not as large as that observed for the outer echoes.

Only moderate to low water content values were encountered in the outer band of the south wall (averaging about 0.4 g./m.^{3} and never exceeding 1 g./m.^{3}); and only moderate water (averaging about 0.9 g./m.^{3} in the wettest portion) was found in the inner band of the south wall. However, the Heiland recorder paper was depleted just before the exit from the south wall into the eye and in an area where the water content was high, so that the water may have been more concentrated just on the inner boundary.

The heaviest concentration of water on the flight, and the highest sustained water content measured during the entire 1958 flight season, was encountered in the east wall. The water content averaged 3.82 g./m.^{3} over the 18 mi. for which data are available and 7.32 g./m.^{3} in the 2-1/2 mi. segment just before the tape broke because of excessive water. It is difficult to tell the precise moment at which the tape broke; however, the water content was in excess of the adiabatic value for at least 12 sec. and reached a value of at least 9.5 g./m.^{3} In addition, part of the hydrometeors were solid - snow showers and snow pellets were reported in this area. There is no question that this was primarily a rain area, with the greater portion of the water coming from above. The apparent discrepancy in figure 17 between the location of the east wall echo and the highest water content was probably due to both the movement of the cloud system and the attenuation of the radar beam as it passed through the heavy cloud matter that lay between the airplane and the rain area. Using radar film collected by Navy reconnaissance planes, Jordan computed the motion of parts of the eye wall to be from 95 tc 130 kt. [9]. As a consequence, it is very possible that the penetration on the east was through the more extensive portion of the wall that is shown on the south in figure 17.

The water content measured on this flight was considerably higher than usual and this was one of the few flights on which the observed water content values approached the adiabatic value. From figure 18 it may be seen that the water content was in excess of 2 g./m.^{3} in about 1/5 of the area traversed within 60 mi. of center and in about 5 percent of the area traversed between

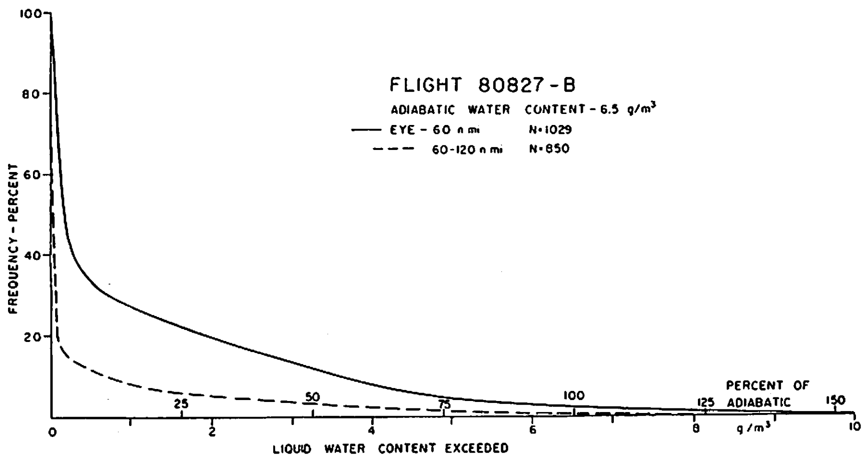

Figure 18. - Percentage of observed water content measurements which exceeded specified amount, hurricane Daisy, August 27.

60 and 120 mi. Despite the unusually high values of water content measured on this flight, only a very small portion (less than 2 percent) of the area traversed had values equal to or greater than the adiabatic value.

There is insufficient storm coverage to study the areal distribution of the water content except perhaps with respect to distance from the storm center. Although the curves in figure 18 suggest that the water content decreased with range, the data for the area from the hurricane eye to 60 mi. are highly colored by the extremely large water content values encountered in the east wall. If these data are omitted, there is very little difference between the two curves. Similarly, the frequency distributions of water content for 20-mi. wide annular rings do not establish any clear-cut range effect (fig. 19). The first annular ring is strongly affected by the extreme conditions in the east wall, but the decrease in the median water content with range suggests that the incidence of cloud-free air and/or cloud matter of very low water content increases with distance from storm center.

Hurricane Helene

Hurricane Helene developed from a weak easterly wave that had moved westward from the region of the Cape Verde Islands. The storm started to intensify very slowly on September 21, 1958 and reached tropical storm classification on the 23d. It continued to deepen slowly but steadily; the central surface pressure was 997 mb. on the 24th, decreasing to 933 mb. on the 27th. The winds also increased slowly but steadily, finally reaching speeds of well over 100 kt. The storm moved northwest until the 27th when it recurved toward the north and northeast from a location just off the coast of the Carolinas.

Water content data collected on September 24 (flight 80924B) have been evaluated. The storm at the time of this flight was located at about 27°N., 72°S. It was still in its fairly early stages, during the period of slow but steady intensification. The eye was about 20 mi. in diameter and fairly well defined. There were spiral bands in all quadrants, the echo pattern taking on a figure-nine configuration elongated along the N-S axis.

Navy reconnaissance planes reported an altostratus overcast with base at about 12,000 ft. and about 4/8 sky coverage of cumuli. The NHRP airplane at 13,000 ft. was frequently between stratified layers and observers reported several cloud decks. The radar film indicates both a great deal of stratiform cloud material and many scattered convective clouds between cloud bands.

Flight 80924B was made between the hours of 1630 and 2100 GMT at 9,000 and 13,000 ft. The water content measurements were very good in quality, and are available for the whole flight except for three periods of 10 to 30 min. when the recorder did not have a paper supply. The air temperatures were above freezing (so that the paper-tape housing was not subject to icing) and there were no reports of solid hydrometeors.

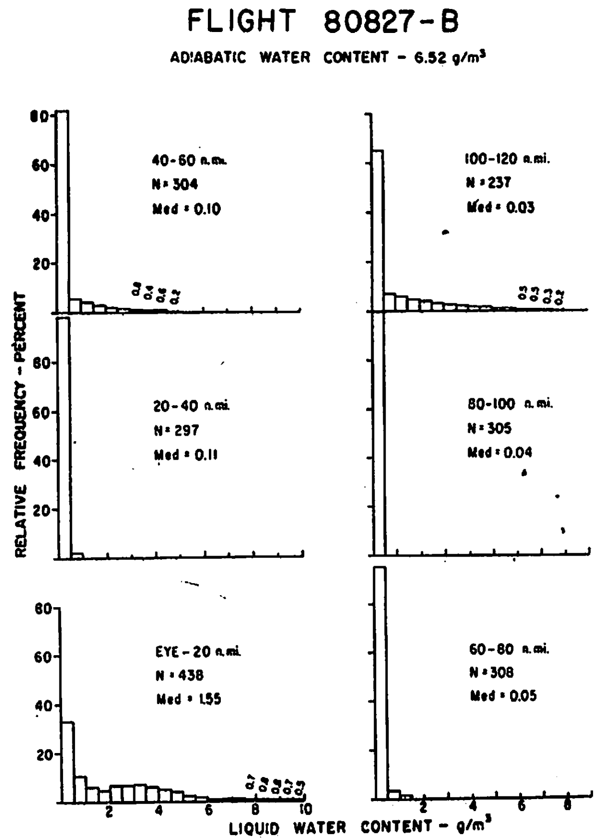

Figure 19. - Frequency distributions of water content (1-sec. means) for 20 mi. wide annular rings in hurricane Daisy on August 27.

The portion of the flight at 9,000 ft. was very short - a single radial traverse through the southwest quadrant. In figure 20 is shown the plot of the average water content over homogeneous sections. Since the radar is mounted on the bottom of the airplane fusilage, only the low-level rain and cloud areas were detected and most of the film record showed only a large, diffuse, and structureless echo. One small cumulus cloud of a band and the wall area were penetrated. The former had passed its prime and was raining out but the water content was quite high - averaging 1.19 g./m.^{3}, with a peak value of 2.70 g./m.^{3} The eye area appears to have been probed in the vicinity of a break in the wall. The water content was generally 0.15 g./m.^{3} or less, with characteristics typical of stratified clouds. Three small convective cells ranging from 1/2 to 1-1/2 mi. in diameter were imbedded in this rain area. The maximum water content (1-sec. mean) measured in these convective cells was 1.36 g./m.^{3}

The penetration at 13,000 ft. was much more extensive. In figure 21 are shown the average water content plotted along the flight path and the radar echo patterns. Only the hard echoes are shown; light structureless echo gen-

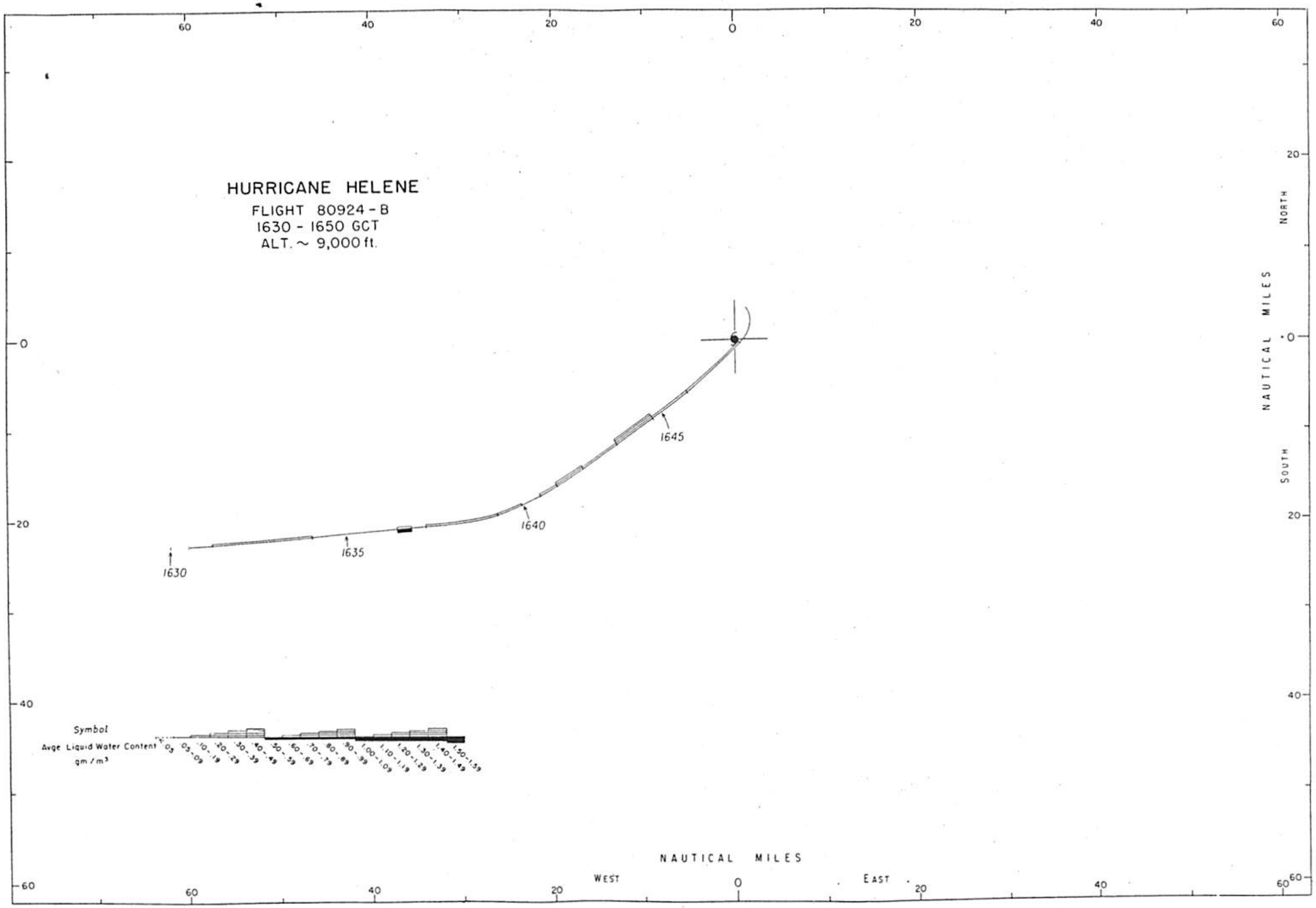

Figure 20. - Average water content over "homogeneous" segments plotted along flight path at 9,000 ft. in hurricane Helene on September 24.

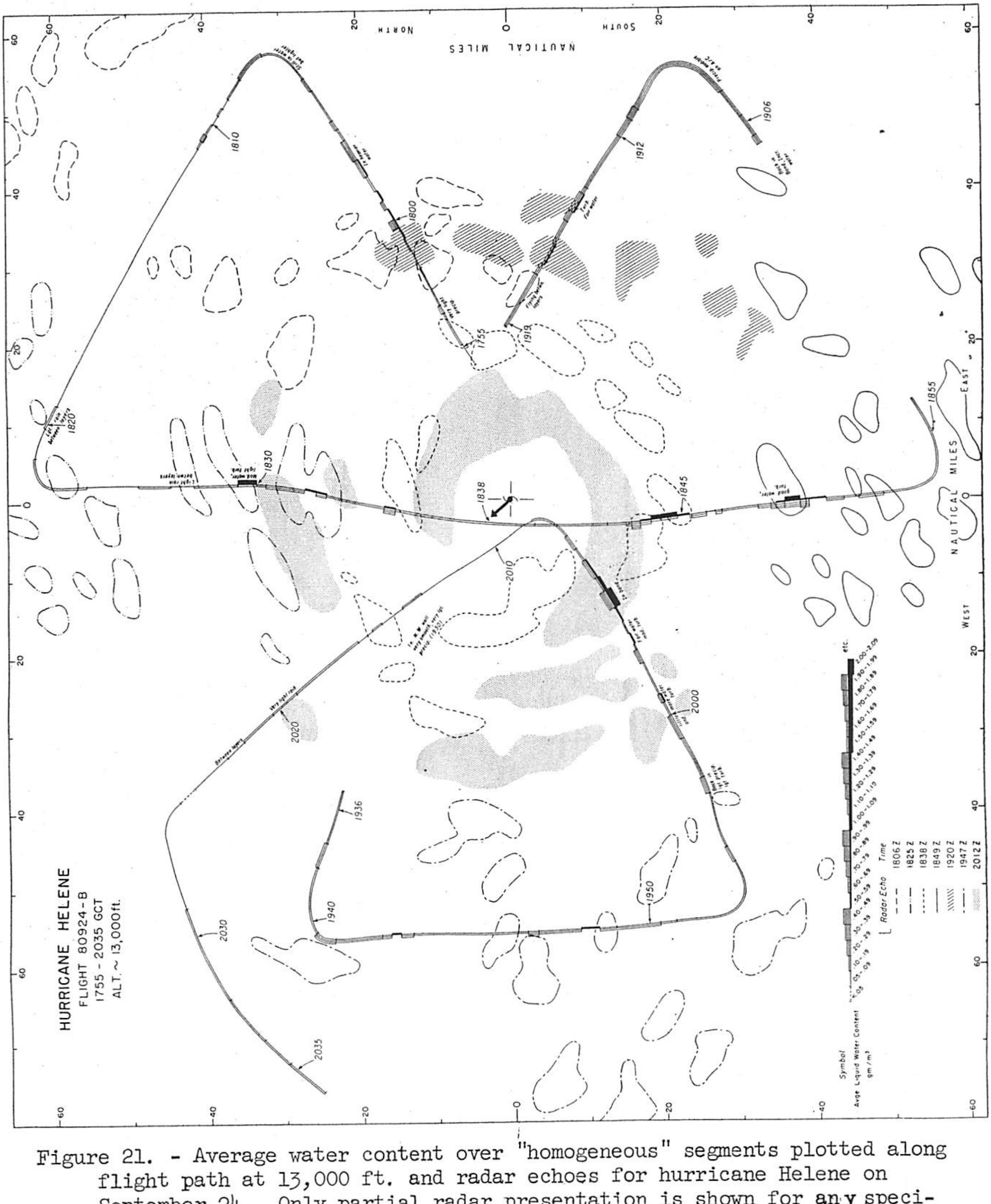

Figure 21. - Average water content over "homogeneous" segments plotted along flight path at 13,000 ft. and radar echoes for hurricane Helene on September 24. Only partial radar presentation is shown for any specified time.

erally filled all interstitial area. The bands were not solid, but rather were lines of small echoes. At least for part of the flight period this was true of the eye-wall band also. The cloud systems were much less organized and the convective clouds much more scattered than normal. It should be pointed out that this storm was in its early stages of intensification at this time and preliminary analyses done by the NHRP staff indicate a rather spread-out wind field - rather than a concentration of the kinetic energy into a narrow zone as is customary in hurricanes.

Lines of echoes were found at about 35 or 40 mi. from the center to the north, east, and south, and at slightly greater distances to the west. The water content measured in two clouds at about 40 mi., one due north and one due south of the storm center, averaged about 1.85 g./m.^{3} over distances of about 2. mi. In each of these clouds there were two sections where the 1-sec. mean water content exceeded 4 g./m.^{3} - with maximum values lying between 4.75 and 5 g./m.^{3} To the east, the water content measured in the small clouds of the line at this radius was lower, with the heaviest cloud sections having average water content of about 0.9 g./m.^{3} The highest 1-sec. means were about 1-1/2 g./m.^{3} The echo conditions were far more scattered in the west than elsewhere in the storm. The water content in the clouds probed to the west was also quite low, averaging in the maximum segments about 0.5 g./m.^{3}

The wall echoes were very broken up on the first half of the flight - the eye was delineated by scattered echoes aligned in a spiral or circular band. Unfortunately the Heiland recorder was without paper supply during the penetrations through the eastern boundary of the eye. Passage through the northern boundary was mainly between convective units, and only the edge of a single one of the small scattered echoes was traversed. The water content in this small cloud averaged about 0.82 g./m.^{3} However, on the south, very wet clouds were probed; the water content averaged 1.67 g./m.^{3} over a 4-mi. stretch in the heart of the wall, and 2.30 g./m.^{3} over the thickest 2-mi. segment. The maximum 1-sec. mean was 5.20 g./m.^{3} (about 77 percent of the adiabatic value).

The southwestern and northwestern sides of the eye were penetrated about 1-1/4 hours after the others. At this time the wall echo was much more continuous than earlier, although it was still entirely open on the northwest. (This may have been due to a change in radar gain setting rather than to a true change in the wall structure.) Passage out of the eye on the northwest was through this open section and the water content was generally less than 0.2 g./m.^{3} Very high water content values were encountered in the southwestern wall. The water content averaged about 1.5 g./m.^{3} over a stretch of nearly 10 mi. (although the water was broken up into a number of clouds or cells) and just under 3 g./m.^{3} in a 2-1/2 mi. segment. The water content exceeded the adiabatic on several occasions; the highest 1-sec. mean was 7.68g./m.^{3}

The rest of the flight was through thin stratiform clouds and/or light rain. The water content through these areas usually averaged between 0.1 and 0.2 g./m.^{3} and on occasion went to 0.3 or 0.4 g./m.^{3} These latter measurements represent a large fraction of the data collected in this storm.

The adiabatic water content for the 9,000-ft. level was 5.25 g./m.^{3} The measurements obtained at this level were all below this amount; the highest average over a 1-sec. period was just 52 percent of theoretical. It can be seen from figure 22 that almost all of the area traversed had water content below 25 percent of theoretical, and all but 6 percent had water content below 10 percent of theoretical.

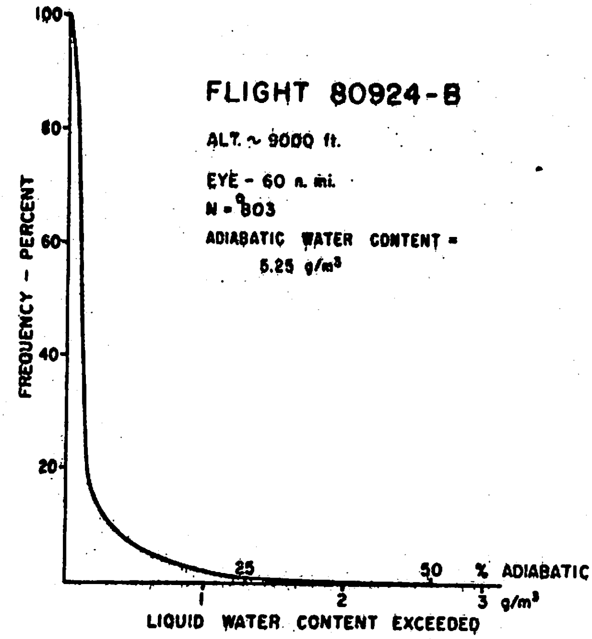

Figure 22. - Percentage of observed water content measurements which exceeded specified amount, hurricane Helene, September 24, 9,000 feet.

Compared to other flights, the 13,000-ft. level had very concentrated water content. Nevertheless, most of the area traversed had water content values well below the theoretical value of 6.70 g./m.^{3} Only 8 percent of the area traversed within 60 mi. from center had water content in excess of 10 percent of theoretical (fig. 23). However, there were some areas in which the water content neared the adiabatic value, and one in which it exceeded the adiabatic. The highest water content encountered was 7.68 g./m.^{3}, 15 percent above the adiabatic water content.

There were too few data collected at 9,000 ft. to examine the variation of water content with range or storm sector; the data for the 13,000-ft. level are shown in figures 24 and 25. There is a fairly consistent tendency for the incidence of high liquid-water content to decrease with range. The left rear quadrant tended to have the highest incidence of high water content values while the front and particularly the left front tended to have the lowest.

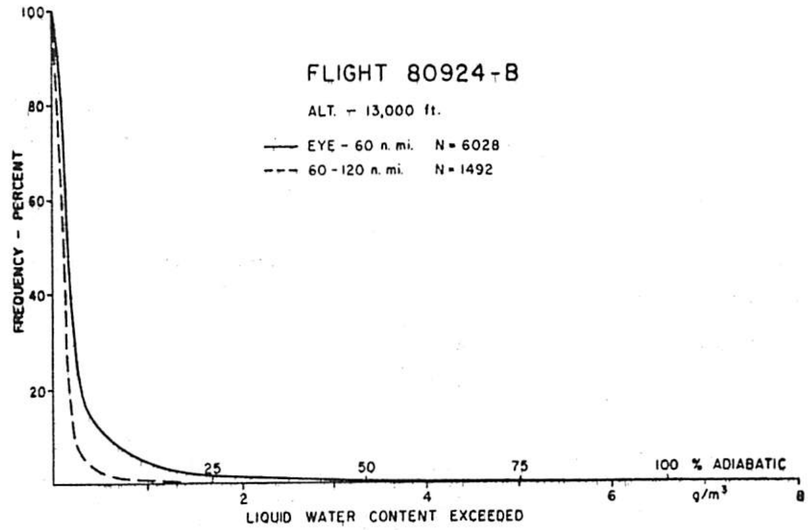

Figure 23. - Percentage of observed water content measurements which exceeded specified amount, hurricane Helene, September 24, 13,000 feet.

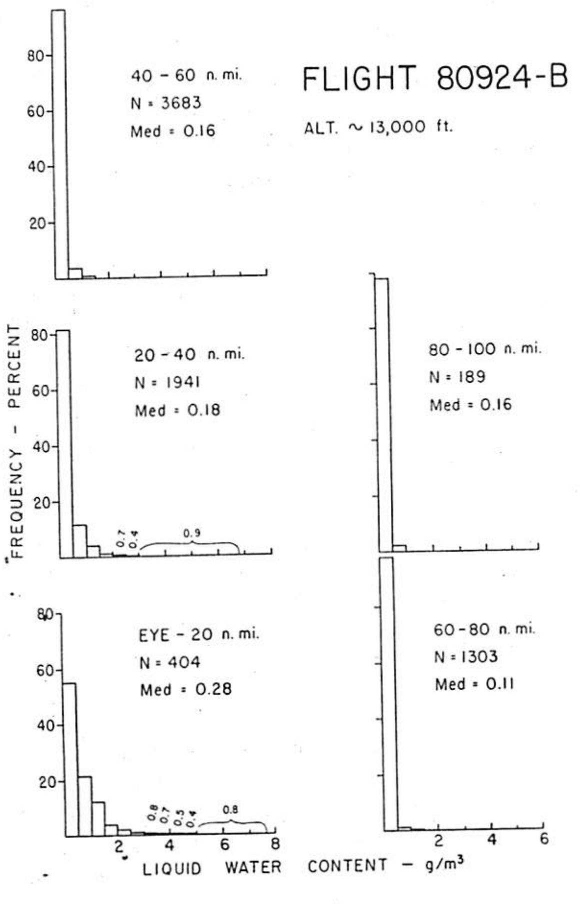

Figure 24. - Frequency distributions of water content (1-sec. means) for 20-mi. wide annular rings at 13,000 ft. in hurricane Helene on September 24.

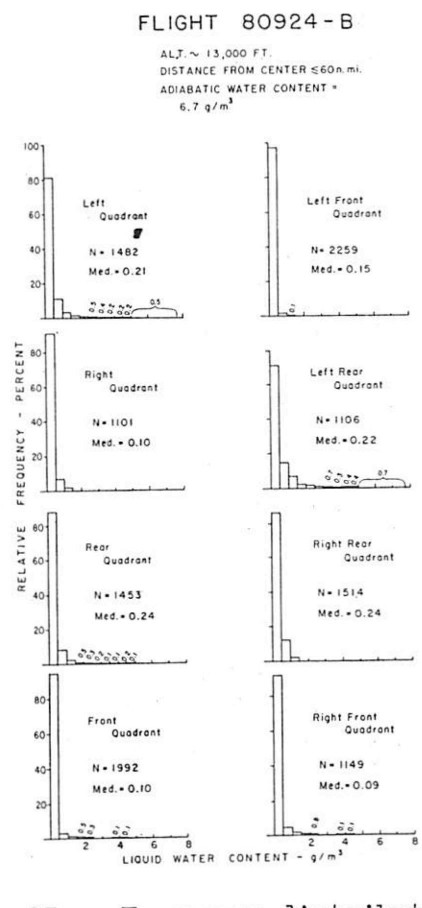

Figure 25. - Frequency distributions of water content (1-sec. means) at 13,000 ft. in hurricane Helene, by quadrant. Division into quadrant according to figure 2.

4. SUMMARY

The outstanding characteristic of the water-content data collected in the hurricane research flights may be summed up in one word - variable. The magnitude of the water measured in clouds covered a wide range, even for a single storm at a single altitude over a relatively short time. To bring order out of chaos required that the water-content measurements be correlated with the cloud structure and its variation. From analyses described above there is little evidence of steady-state conditions in the water distributions. Because of the discontinuous and transient nature of the water, even the large volume of data that has been evaluated represents a small sample.

The data were analyzed individually for each flight for several reasons: the need to correlate water content and cloud systems; the large mass of data involved; the sizable differences between the data collected on various storm flights. The latter problem, i. e., the differences between flights, is not too surprising since they were made at several different altitudes as well as into several storms which were in different stages of their development. Individual cases have been described above; those gross characteristics which appear to be less closely linked with the specific features of a storm are summarized below.

The cloud water content values were surprisingly low; in only a few instances were they over 3 or 4 g./m.^{3}, and the bulk of the measurements were below 1 or 2 g./m.^{3} Water content consistent with an undiluted adiabatic cloud model was seldom found, and almost all of the measured values were less than 50 percent of that expected for such a model. In all the hours of flight, there were only three instance on which the water content equaled or exceeded the adiabatic value and one of these occurred in an area of heavy rain with the bulk of the water (which was mixed with snow and ice pellets) falling from above. Admittedly some of the data were collected at sub-zero temperatures and part of the hydrometeors were solid. However in these cases the ambient air was less than 5° below freezing and it is doubtful that much of the realized vapor could be in the solid phase except in cases where snow and rain were falling from above.

The incidence of cloud-free air, or low-water-content clouds, tended to increase and the incidence of moderate to high-water-content clouds tended to decrease with distance from the storm center. The areal density of convective clouds decreased with range (evident from radar as well as water data) and therefore the probability of penetrating areas of high water content must also decrease when the flight path is established on a geometric pattern (as was generally true on these flights). Although on some flights the highest water contents encountered seemed to decrease with range, there were some noteworthy exceptions and any suggested trend for the cloud water to be less concentrated in more distant regions may have been a reflection of the decrease in the probability of intercepting the cores of heaviest concentration.

The distribution of the water in the various azimuthal sectors was not consistent from storm to storm; the data suggest that it may be a function of the age or stage of development. Two flights were through hurricanes in their early stages of development and one was through a tropical storm. In these three the heaviest concentration of water was found in the rear sectors of the storm. On the single flight through a hurricane which had passed its peak (Carrie 1957), the heaviest concentration was found in the forward sections of the storm.

Some of the data suggest that the water content of the clouds in a cloud band may increase downstream, that is from the outer end of a cloud line inward as it spirals cyclonically toward the center. However there were not sufficient data analyzed to establish this trend and it is mentioned here only as a possibility for future study. On the three flights for which data are available in all quadrants, the clouds were more scattered, smaller, and had a lower areal density in the west than in the east, increasing slightly in number and size from northwest to southwest.

The data presented above permit, for the first time, the use of observed values in the estimates of water and energy balances. Moreover these studies suggest that meso-analyses of the cloud and water distributions using flow patterns and wind distributions obtainable from other sources in the observational program might provide additional insight into the basic hurricane mechanisms.

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